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# Preserving logistical support for deployed battle groups in an Anti-Access, Area Denial (A2AD) environment

Colburn, Brian D.

Monterey, California: Naval Postgraduate School

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# NAVAL POSTGRADUATE SCHOOL

**MONTEREY, CALIFORNIA**

# THESIS

**PRESERVING LOGISTICAL SUPPORT FOR DEPLOYED BATTLE GROUPS IN AN ANTI-ACCESS, AREA DENIAL (A2AD) ENVIRONMENT**

by

Brian D. Colburn

September 2015

Thesis Advisor: Emily M. Craparo
Second Reader: W. Matthew Carlyle

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The U.S. Navy's at sea replenishment system is a mobile supply line designed to support the deployed Carrier Task Force (CTF)/Cruiser/Destroyer (CRUDES) Surface Action Group (SAG) and forward deployed units while at sea. In the 7th Fleet area of responsibility the main component of the mobile supply line, the Combat Logistics Force (CLF) ship, has become a possible target with the development of the anti-ship ballistic missile (ASBM). With the ability to target and disable a CLF with an ASBM, an enemy can now disable a deployed CTF/CRUDES fleet by eliminating its required replenished resources, rendering it combat ineffective and more vulnerable to attack.

With the goal of preserving the CLF's capabilities to perform its mission while not subjecting it to an ASBM threat, we consider the possibility of utilizing a "mini-CLF" to shuttle fuel between CLFs operating in a safe environment and warships operating in a threat zone. The alternatives this thesis examines are: (1) analyze the feasibility of using Littoral Combat Ship/Joint High-Speed Vessel, reconfigured as shuttles to transport underway replenishment requirements from the CLFs to the CTF/CRUDES fleet while deployed in the Western Pacific, and (2) analyze requirements for development of a new class of ships to support the CTF/CRUDES SAG while deployed in the Western Pacific.

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**PRESERVING LOGISTICAL SUPPORT FOR DEPLOYED BATTLE GROUPS IN AN ANTI-ACCESS, AREA DENIAL (A2AD) ENVIRONMENT**

Brian D. Colburn
Lieutenant Commander, Supply Corps, United States Navy
B.S., San Diego State University, 2001

Submitted in partial fulfillment of the
requirements for the degree of

**MASTER OF SCIENCE IN OPERATIONS RESEARCH**

from the

**NAVAL POSTGRADUATE SCHOOL**
**September 2015**

Author: Brian D. Colburn

Approved by: Emily M. Craparo
Thesis Advisor

W. Matthew Carlyle
Second Reader

Robert F. Dell
Chair, Department of Operations Research

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# ABSTRACT

The U.S. Navy's at sea replenishment system is a mobile supply line designed to support the deployed Carrier Task Force (CTF)/Cruiser/Destroyer (CRUDES) Surface Action Group (SAG) and forward deployed units while at sea. In the 7th Fleet area of responsibility the main component of the mobile supply line, the Combat Logistics Force (CLF) ship, has become a possible target with the development of the anti-ship ballistic missile (ASBM). With the ability to target and disable a CLF with an ASBM, an enemy can now disable a deployed CTF/CRUDES fleet by eliminating its required replenished resources, rendering it combat ineffective and more vulnerable to attack.

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# TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

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# LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| A2AD | Anti-Access, Area Denial |
| AOR | Area of Responsibility |
| ASBM | Anti-Ship Ballistic Missile |
| ARL | Aft RAS Lanes |
| BBLS | Barrels |
| CINCLANTFLT | Commander in Chief, U.S. Atlantic Fleet |
| CG | Guided Missile Cruiser |
| CLF | Combat Logistics Force |
| CRUDES | Cruiser/Destroyer |
| CTF | Carrier Task Force |
| CVL | Small Aircraft Carrier |
| CVN | Aircraft Carrier (Nuclear) |
| DDG | Guided Missile Destroyer |
| DF-21D | Dong-Feng-21D |
| DFM | Diesel Fuel, Marine |
| DL-RASM | Dual Lane Replenishment At-Sea Model |
| DOE | Design of Experiments |
| FOS | Forward Operating Stations |
| FRL | Forward RAS Lanes |
| GFSMP | Global Fleet Station Mission Planner |
| JHSV | Joint High-Speed Vessel |
| JP5 | Aviation Fuel |
| KTS | Knots |
| LCS | Littoral Combat Ship |
| LHD | Amphibious Assault Ship |
| ITP | Intermediate Transit Points |
| NNFM | New Navy Fighting Machine |
| NOLH | Nearly Orthogonal Latin Hypercube |
| NPS | Naval Postgraduate School |
| OPNAV | Office of the Chief of Naval Operations |

| | |
|---|---|
| PRC | People’s Republic of China |
| RAS | Replenishment at Sea |
| RASP | Replenishment At-Sea Planner |
| SAG | Surface Action Group |
| T-AKE | Auxiliary Dry Cargo and Ammunition Ship |
| T-AO | Fleet Oiler |
| USPACFLT | United States Pacific Fleet |

# EXECUTIVE SUMMARY

The U.S. Navy's at sea replenishment system is a mobile supply line designed to support the deployed Carrier Task Force (CTF)/Cruiser/Destroyer (CRUDES) Surface Action Group (SAG) and forward-deployed units while at sea. In the 7th Fleet area of responsibility the main component of the mobile supply line, the Combat Logistics Force (CLF) ship, has become a possible target with the development of the anti-ship ballistic missile (ASBM). With the ability to target and disable a CLF with an ASBM, an enemy can now disable a deployed CTF/CRUDES SAG by eliminating its required replenished resources, rendering it combat ineffective and more vulnerable to attack.

With the goal of preserving the CLF's capabilities to perform its mission while not subjecting it to an ASBM threat, we consider the possibility of utilizing a "mini-CLF" to shuttle fuel between CLFs operating in a safe environment and warships operating in a threat zone. This thesis: (1) analyzes the feasibility of using a Littoral Combat Ship/Joint High-Speed Vessel, reconfigured as a shuttle to transport underway replenishment requirements from the CLFs to the CTF/CRUDES SAG while deployed in the Western Pacific, and (2) analyzes requirements for development of a new class of ships to support the CTF/CRUDES SAG while deployed in the Western Pacific.

During a peacetime scenario, we study the impact of three parameters on our ability to refuel deployed combatant ships: shuttle speed, shuttle deliverable fuel capacity, and available number of shuttles. In order to efficiently explore this design space, we apply a three-factor custom nearly orthogonal Latin hypercube design of experiments to our Dual Lane Replenishment At-Sea (RAS) Model (DL-RASM).

In our peacetime scenario, we demonstrate how the deliverable fuel quantity and number of shuttles affects the shuttles' ability to support the deployed forces. Our analysis does not indicate a strong correlation between increased shuttle speed and an improved ability to support the warships. Results indicate six shuttles with 1.5M gallons of deliverable fuel each can sustainably support the deployed CTF/CRUDES SAG in our scenario. We also find that the shuttles make heavy use of the ports of Sasebo and

Okinawa, Japan, and Subic Bay, Philippines for refueling, while only making limited use of the aft RAS lanes (ARLs) and CLFs. While this heavy usage of ports is completely reasonable given the distances involved to the ARLs, it does invite the potential for disruption due to the fact that these ports lie within the Anti-Access, Area Denial (A2AD) environment.

In our wartime scenario, we consider a situation in which access is denied for all ports except Guam. In this situation, the shuttles must refuel at the ARLs, while the CLFs are able to refuel at Guam. Our analysis indicates that the moderate number of shuttles required to support a peacetime scenario can allow some resiliency should a wartime scenario ensue. However, eight shuttles are required to provide sustainable support in such a wartime scenario.

Indeed, perhaps our most interesting findings result from eliminating the vulnerable ports as a replenishment option for the shuttles. We find that the required number of shuttles during peacetime cannot support the warships without port access. Additionally, we find that the efficiency of delivering fuel is dependent upon the number of shuttles available and that efficiency and effectiveness are competing objectives that must be balanced.

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# I. INTRODUCTION

As the U.S. military and its leaders continue to evaluate how to ensure the United States has a superior force, and to preserve or regain our military advantages, the Navy has identified a possible roadmap to its future.

"Of Chief of Naval Operations Admiral Jonathan Greenert's three tenets, 'Warfighting First' is at the top, and that is no accident" (Rowden, Gumataotao, & Fanta, 2015, p.18). With senior military officers like VADM Rowden, RADM Gumataotao and RADM Fanta publishing concepts like "distributed lethality" as the way to employ our naval assets in the future, we must give attention to how to support this distributed mode of operations. "For more power in more places, the Navy should increase the offensive might of the surface force and employ ships in dispersed formations known as 'hunter-killer surface action groups'" (Rowden et al., 2015, p. 18).

The concept of "distributed logistics" to support such "distributed lethality" is already being addressed by students at the Naval Postgraduate School in Monterey, CA. As identified by LCDR Ellis in a paper for the Joint Campaign Analysis class,

> Legacy logistics solutions are ill-suited for supporting a large fleet of small units operating in an Anti-Access, Area Denial (A2AD) region. A Distributed Logistics concept is proposed, serving as a hybrid of traditional established logistics bases (ELBs) and Combat Logistics Force (CLF) routes, augmented with a network of small and temporary Expeditionary Support Bases (ESBs). These ESBs are supplied with the Combat Support Shuttles (CSSs), which could be new ships, or a potential use for existing platforms such as the Littoral Combat Ship (LCS) or Joint High Speed Vessel (JHSV). (Ellis, 2013)

## A. BACKGROUND

The U.S. Navy's at-sea replenishment system is a mobile supply line designed to support the deployed Carrier Task Force (CTF)/Cruiser/Destroyer (CRUDES) Surface Action Group (SAG) and forward deployed units while at sea. In the 7$^{th}$ Fleet area of responsibility (AOR) the main component of the mobile supply line, the CLF ship, has become a possible target with the development of the Dong-Feng-21D (DF-21D), a Chinese-developed anti-ship ballistic missile (ASBM). With the claimed ability to target and disable our current CLF fleet with a DF-21D, if within range, an enemy can now disable a deployed CTF/CRUDES SAG by eliminating its required replenished resources, rendering it combat ineffective and more vulnerable to attack.

With the goal of preserving the CLF's ability to perform its mission while not subjecting it to an ASBM threat, we consider the possibility of utilizing a "mini-CLF" to shuttle fuel between CLFs operating in a safe environment and warships operating in a threat zone. This thesis: (1) analyzes the feasibility of using existing assets such as LCS/JHSV, reconfigured as shuttles to transport underway replenishment requirements from the CLFs to the CTF/CRUDES SAG while deployed in the Western Pacific, and (2) analyzes requirements for development of a new class of ships to support the CTF/CRUDES SAG while deployed in the Western Pacific.

Examination of a shuttle's performance and ability to support the deployed CTF/CRUDES SAG is based solely on the potential for a shuttle to connect with and transfer commodities from a port or CLF outside of the threat area to the deployed CTF/CRUDES SAG in the assigned AOR.

## B. OBJECTIVES

It has been suggested that LCS/JHSV could act as a shuttle supplying the deployed CTF/CRUDES SAG adequately. This thesis seeks to identify if that is possible for our scenario, and if not, what would be the configuration requirements for a shuttle to perform this mission. Such a shuttle could act as an intermediate CLF less vulnerable to attack in an A2AD environment due to decreased size and possibly increased speed relative to traditional CLF vessels. To accomplish this, we develop an optimization model that prescribes a refueling schedule for a set of warships, shuttles, and CLF ships, with the goal of maximizing on-station time for the warships while keeping the CLF ships out of harm's way.

This thesis contributes a valuable network performance assessment and alternative to the 7th Fleet and Operational Navy (OPNAV) leadership. The tools developed for this thesis can be easily adapted to evaluate shuttle performance under a host of other employment parameters. The resultant understanding of how shuttle deployment affects a supply network's ability to support mission critical replenishment will be invaluable in future systems analysis and CLF ship development.

## C. SCOPE, LIMITATIONS, AND MODEL ASSUMPTIONS

### 1. Scope

This thesis supports unpublished, ongoing work by U.S. Pacific Fleet (USPACFLT) in efforts to provide feasible options to resolve the identified issues of continued logistic support to deployed forces in the Western Pacific and the South China Sea. This research analyzes the potential for and design requirements of a shuttle as a delivery ship between a CLF ship or port and deployed CTF/CRUDES SAG assets in the 7th Fleet AOR while preserving the safety of the CLF ship now potentially subject to the threat presented by the A2AD environment.

### 2. Limitations

Our model only accounts for the fuel commodity required by a deployed CTF/CRUDES SAG during a predetermined, fixed time horizon. It does not account for the consumption of stores commodities or ordnance that may require replenishment due to expenditure. Our scenarios consider a predetermined fleet composition in an identified AOR, excluding the addition or subtraction of assets and the possibility of external demands on the CLF/Shuttle force in the model.

### 3. Model Assumptions

We assume the following in order to produce a mathematical model and a realistic scenario for evaluating the effectiveness of numerous design criteria of a shuttle ship to be the "delivery boy" between current CLF and deployed CTF/CRUDES assets:

- The DF-21D threat keeps large ships from safely operating in the South China Sea/Western Pacific. Large ships include the Aircraft Carrier (Nuclear) (CVN), Amphibious Assault Ship (LHD), and Auxiliary Dry Cargo and Ammunition Ship (T-AKE)/Fleet Oiler (T-AO). This drives the design requirement for the production of a smaller shuttle ship to more safely operate within the DF-21D threat range based solely on the size restriction.

- A deployed CTF/CRUDES SAG requires resupply to continue operations at the FOSs. This drives the requirement for fuel commodities to be transported through the network of arcs and nodes for consumption by the deployed CTF/CRUDES assets.
- For simplicity, we are only accounting for liquid fuel in this initial analysis.
- The quantity of JP5 (aviation fuel) required by the airwing to conduct aircraft carrier flight operations is calculated into the liquid fuel requirements by combining Diesel Fuel, Marine (DFM) and JP5 quantity requirements into a single liquid fuel quantity measured in barrels (bbls). This allows for the complete accounting of throughput of liquid fuel to a CTF as an aircraft carrier is a nuclear powered vessel and does not consume large quantities of DFM.
- All ships in an assigned battle group stay within close proximity of each other unless an individual ship's burnable fuel quantity falls below the safety fuel quantity level, if this occurs, the individual ship can detach from the CTF/CRUDES SAG and operate independently to navigate to a forward replenishment at-sea (RAS) lane (FRL) or port to receive fuel.
- Our initial analysis considers peacetime operations. Peacetime operations typically have a lengthier time horizon, therefore testing the model in a sustained optimization environment as opposed to a shorter time horizon wartime scenario.

## D. CONTRIBUTIONS

This thesis contributes to the ongoing study of CLF ships and their utilization in the fleet. It develops the Dual Lane RAS Model (DL-RASM), an optimization model designed to evaluate a possible method to preserve logistic support to a deployed CTF/CRUDES SAG operating within an anti-access, area denial (A2AD) environment. Through optimization and sensitivity analysis, we identify critical design characteristics for a next generation of CLF ship to provide improved safety to the current CLF fleet configuration, provide sufficient support to deployed assets operating in an A2AD environment, improve resiliency in the RAS logistics network, and provide improved future support of a changing fleet configuration as adversaries move to master the seas in the littorals.

# II. LITERATURE REVIEW

Several prior studies have investigated design and utilization of CLF ships to support U.S. assets afloat. These include both theses and operational logistics models. While this prior work has been extremely useful and has brought about improvements in the at-sea replenishment process, none of these works have considered the threat to the highly valued assets in the CLF ship fleet. Work has been completed focusing on the next composition of the U.S. Navy taking into account the developed A2AD threat and the move of the at-sea battle into littoral waters, but it has not yet provided answers of how to support this new fleet while at sea. We now give an overview of prior work that considers aspects of these subjects; no prior study combines the topics of at-sea replenishment of the current or future naval fleet and the threat of the A2AD environment.

## A. CLF FLEET COMPOSITION COMPARISON

Givens (2002) used an optimization-based assessment model to compare two top CLF alternatives published by the Commander in Chief, U.S. Atlantic Fleet (CINCLANTFLT) report in 2001. It was based on Borden (2001) and was the first to compare and optimize the configuration and loading of CLF ships to determine the CLF fleet composition based on a deterministic model. The results reveal the best way to utilize CLF assets to achieve full force potential comparing details that include stock levels maintained, prepositioning of CLF ships, and the minimum number of ships required. While these models include a global view of navigable world sea routes, forward positioned commodities, and the network between theaters, they do not consider the developing threat to the CLF ship and the impact it could have on the ability of deployed CTF/CRUDES assets to be replenished at sea if a CLF was lost.

## B. CLF PLANNER

With the success of the early optimization models, additional models were developed that assess specific aspects of logistics support to deployed naval forces. Models such as Global Fleet Station Mission Planner (GFSMP) (Spitz, 2007) and “Navy Combat Logistics Force” (CLF) Planner (Brown and Carlyle, 2008) are just two (Brown, Carlyle, Kelton, Kline & Salmeron, 2009). However, the CLF Planner became the more adopted tool and has been applied to exercises developed by U.S. Commander, Second Fleet, exhibiting significant improvements over manual planning (Brown et al., 2009). Morse (2008) uses this model in its most recent refinement developed by Doyle (2006), in parallel to a concurrent OPNAV N-42 Combat Logistics Force Zero-Baseline Review, to provide additional insights into asset allocation and utilization for specific scenarios. It demonstrates that the model can be used as a decision analysis tool and that it could be adapted to any scenario, fleet-specific or global, to provide CLF fleet analysis as well as operational CFL requirements planning (Morse, 2008). In a time when the CLF was comprised of 31 ships of five basic ship types and was being transformed to 30 ships of three basic types by 2014, Morse's work was pivotal in providing essential decision making information to OPNAV N-42. While Morse's thesis does a thorough job of examining past analysis for CLF fleet sizing and expands the model and information base pertinent to the subject, it does not take into account the developing threat of the current A2AD environment, then in its infancy. Our optimization model could be adapted and applied as Morse's model was and address a solution to the A2AD threat to our active CLF. It also provides a next generation analysis tool to be expanded upon and utilized in the future of CLF planning.

## C. REPLENISHMENT AT-SEA PLANNER

Brown, Carlyle and Burson's Replenishment At-Sea Planner (RASP) (2010) was the next generation of optimization model designed more for the everyday CLF scheduler, and it is based on CLF Planner. However, where CLF Planner addresses the strategic question of how many and what type of supply ships to build in the future on a macro level, RASP evaluates CLF employment at an operational level (Stewart, 2013). It evaluates the ability of a single ship in a region to replenish multiple ships over a four-hour window. In 2012, Naval Postgraduate School (NPS) Research Associate, Anton Rowe, author of much of the detailed code that makes the Replenishment at Sea Planner (RASP) work, stated that "the Replenishment at Sea Planner creates a schedule that minimizes the distance that supply ships have to travel and identifies routes that allow vessels to travel at speeds optimal to fuel conservation" (Stewart, 2013). While RASP optimizes a schedule for CLF support of naval assets afloat in a region, saving the military millions in fuel costs, it only identifies the most efficient means based on its inputs to meet the deployed fleet's needs. Our model accomplishes this while accounting for the safety of the CLF ship in its daily operations.

## D. DEVELOPMENT OF THE A2AD ENVIRONMENT

The present era of warfare at sea is defined by missile technology. DF-21D has become the primary threat to the larger ships in our fleet, and with its range and targeting capability, it is a substantial threat the U.S.'s ability to continue to operate its navy in the manner in which it is accustomed. While DF-21D is not the only missile threat to our fleet afloat (Ross & Harmon, 2012), it is the threat that defines operational parameters for the CLF assets used in our optimization model. While Ross and Harmon (2012) utilize a range of 1500 km for DF-21D, the area cover range images for the DF-21D as of 2010, depicted in Figure 1, allow for a range of 2000 km (shaded in yellow).

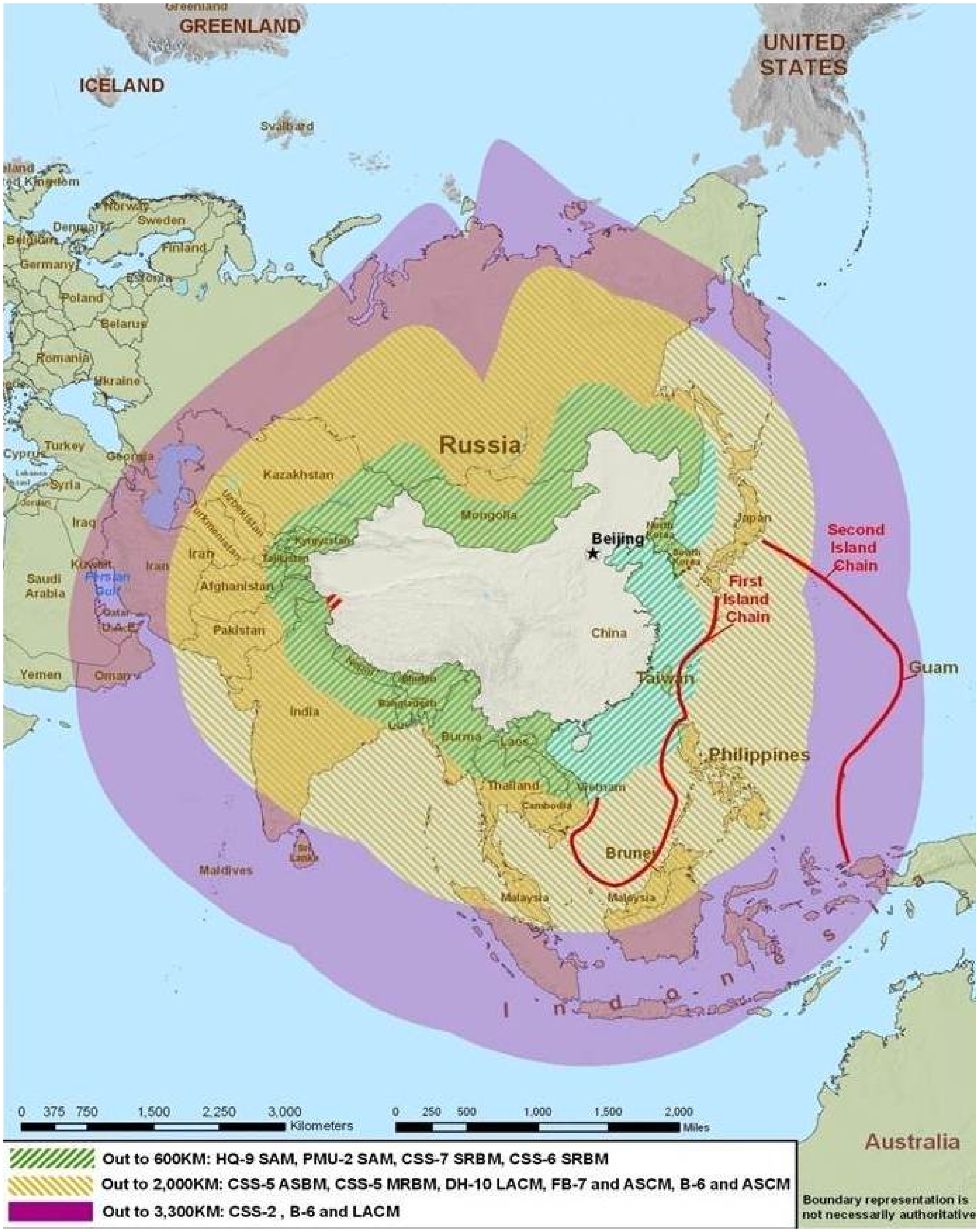


Figure 1. Range rings for the Chinese DF-21D (listed as CSS-5) ASBM and other conventional anti-access capabilities (from Collins & Erickson, 2010)

More recent information supports the expanded range out to 2000 km (Jane’s Strategic Weapons Systems, 2015). This expanded range further limits the operational area of the CLF assets to preserve their safety and further complicates the logistical support problem.

As can be seen in Figure 2, a satellite image published in the Want China Times (2013) reveals two large craters on a 200-meter-long by 33-meter-wide white platform in the Gobi desert, used to simulate the flight deck of an aircraft carrier. The photo was first posted on SAORBATS, an Internet forum based in Argentina. Military analysts at the time believed the craters were created by China's DF-21D anti-ship missile, dubbed the "carrier killer" (Want China Times, 2013).

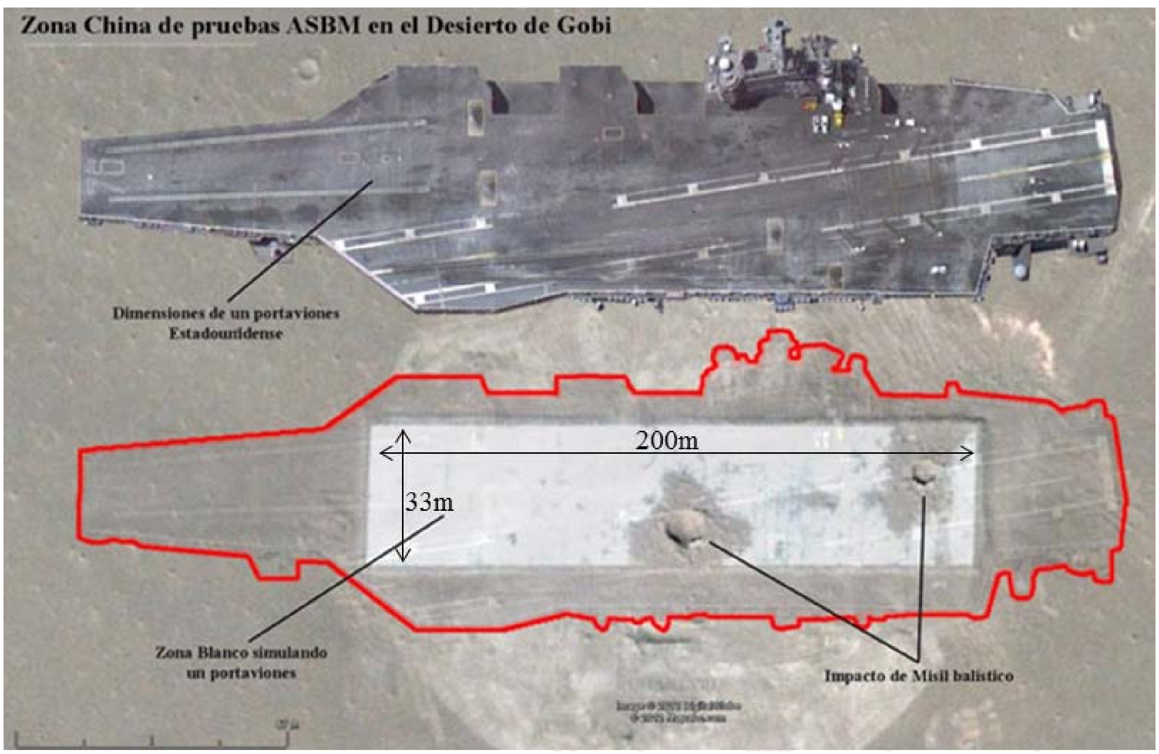


Figure 2. The test (from Want China Times, 2013)

This realized threat has raised the question, how do we protect our highly valued CLF assets but still provide logistic support for our deployed assets, seeing as our current CLF fleet are approximately the dimensions listed in Figure 2? Table 1 underscores this threat by showing the dimensions of the T-AKE and T-AO utilized in the DL-RASM model.

Table 1. CLF ship dimensions (from Jane's Fighting Ships, 2015)

| | Lewis and Clark (T-AKE) | Henry J. Kaiser (T-AO) |
|---|---|---|
| Length | 210.0 m (689.0 ft) | 206.5 m (677.5 ft) |
| Beam | 32.2 m (105.6 ft) | 29.7 m (97.4 ft) |

## E. NEW NAVY FIGHTING MACHINE

Although the current U.S. naval fleet needs to change to counter the evolving missile threat and the transition of sea warfare to the littorals using missile boats, the logistics aspect of how to support the new fleet has escaped most analyses performed to date. Hughes (2009) published such a paper identifying the concept of the NNFM Green Water Fleet. Table 2 depicts the composition of the proposed fleet to combat the emerging threat of our adversaries in the littorals.

Table 2. NNFM Green Water Fleet Composition (from Hughes, 2009)

| NNFM Green Water Fleet | |
|---|---|
| Ship or Craft | Number of Units |
| Coastal Combatant | 30 |
| Offshore Patrol | 160 |
| Fleet Station Ship | 12 |
| Inshore Patrol | 400 |
| Gunfire Support | 12 |
| Fast Mine Warfare (MIW) | 12 |
| Anti-Submarine Warfare (ASW) | 12 |
| CVL (Green Water Fleet) | 8 |
| Coastal Combatant Tender | 2 |
| Total | 648 |

Utilizing current force deployment concepts of 1/3 of the fleet deployed at any point in time, this fleet composition results in approximately 216 ships requiring at-sea support, a considerable increase over today's numbers (Status of the Navy, 2015). In addition to being extremely vulnerable to attack, the current CLF design is limited in the number of ships it can service in a given period of time. Thus, a new shuttle ship can assist in supporting the transformation of the U.S. naval fleet and allow diversification of the fleet while decreasing commodity risk and increasing logistics network resiliency.

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# III. MODEL AND SCENARIO DEVELOPMENT

This chapter introduces the Dual Lane Replenishment At-Sea Model (DL-RASM). DL-RASM is a discrete-time mixed integer linear program that optimizes the ability of a set of shuttles and CLF ships to provide required liquid fuel logistic support to deployed warships for a given planning horizon. DL-RASM prescribes the movement and refueling schedules of a set of warships, shuttles, and CLFs. It incurs penalties for each barrel of fuel shortage that warships, shuttles or CLF ships experience below prescribed safety stock levels, and it accumulates rewards for every barrel of fuel transferred and transmitted through the network, as well as for every time period a warship spends on a forward operating station (FOS). DL-RASM is a network-based model; its nodes consist of forward operating stations, forward RAS lanes (FRLs), intermediate transit points (ITPs), aft RAS lanes (ARLs), and ports. It derives its name from the fact that there are two lanes for replenishment, forward and aft. A schematic representation of the nodes and arcs within the network is provided in Figure 3, and it indicates which nodes are in the threat area, as well as which nodes and arcs are used by the warships, shuttles and CLF ships.

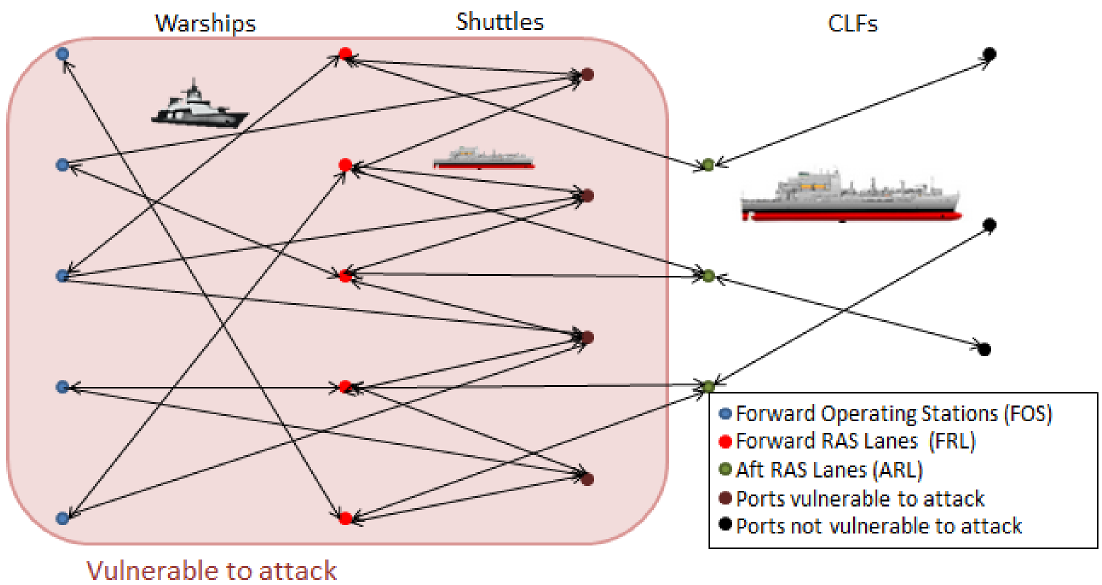



Figure 3. Schematic representation of the nodes, arcs, and threat area modeled by DL-RASM. Warships only visit forward operating stations and forward RAS lanes, shuttles visit forward RAS lanes, aft RAS lanes, and ports in the threat area and CLFs visit aft RAS lanes and ports outside the threat area.

## A. ASSUMPTIONS

We make the following assumptions in order to produce a realistic mathematical model and accompanying input data:

- All ships in a battle group must travel together as a unit, unless a ship encounters a fuel shortage of sufficient severity. If this occurs, that ship may separate from the battle group in order to obtain fuel. To enforce the requirement that all ships in a battle group remain together, we require that each ship be collocated with its battle group's carrier unless low on fuel. This may involve creating a fictitious carrier for any battle group that does not contain a carrier.
- Warships have a single fuel tank containing burnable fuel. Shuttles and CLFs have two fuel tanks: one containing burnable fuel, and one containing deliverable fuel. Each shuttle can transfer fuel from its deliverable fuel tank into the burnable fuel tank of a warship or into its own burnable fuel tank. Each CLF ship can transfer fuel from its deliverable fuel tank into the burnable fuel tank of a shuttle, the deliverable fuel tank of a shuttle or into its own burnable fuel tank.
- For a RAS event to occur, the relevant ships must be collocated at a FRL or ARL for a sufficiently long time.

- For modeling purposes, FOSs and FRLs are collocated; however, when a warship is performing RAS operations, it occupies the FRL node and is not rewarded for operational time at the FOS.
- During peace-time operations, RAS events only occur during daylight time periods. This is representative of actual operational restrictions currently practiced during peacetime operations.
- The combat fleet, shuttles and CLF fleet do not suffer any losses during the scenario. That is, all ships remain available throughout the planning horizon.
- Each warship, shuttle, and CLF ship consumes fuel at the same rate at each period in time, unless it is in port.
- Once a ship enters port, it must remain in port for a prescribed number of time periods.
- Requirements outside of the AOR and scenario do not impact the availability of assets.

## B. DUAL LANE, REPLENISHMENT AT-SEA MODEL FORMULATION

### 1. Indices and Sets [Approximate Cardinality]

$bg \subseteq WxG$ warship *w* belongs to battle group *g* (used only in preprocessing)
$c \in C$ CLF ships [2]
$f, f' \in F \subseteq N$ forward operating station nodes [7]
$g \in G$ battle groups [2]
$n, i, j \in N$ nodes [~30]
$p, p' \in P \subseteq N$ port nodes [6]
$r, r' \in R \subseteq N$ RAS lane nodes [10]
$s, s' \in S$ shuttle ships [~3-8]
$t, t', t'' \in T$ time periods [~20]
$t \in D \subseteq T$ daylight time epochs [~90]
$w, w' \in W$ warships [~10]
$(i, j) \in ac \subseteq NxN$ arc $(i, j)$ can be traversed by CLF ships
$(i, j) \in as \subseteq NxN$ arc $(i, j)$ can be traversed by shuttle ships
$(i, j) \in aw \subseteq NxN$ arc $(i, j)$ can be traversed by warships
$(w, w') \in carrier \subseteq WxW$
warship $w'$s carrier is warship $w'$
$(t, t', c, i, n) \in dC \subseteq TxTxCxNxN$
if CLF ship *c* departs node *i* at time *t*, it will arrive at node *n* at time $t'$
$(t, t', s, i, n) \in dS \subseteq TxTxSxNxN$
if shuttle ship *s* departs node *i* at time *t*, it will arrive at node *n* at time $t'$
$(t, t', w, i, n) \in dW \subseteq TxTxWxNxN$

if warship $w$ departs node $i$ at time $t$, it will arrive at node $n$ at time $t'$

$(w,t,n) \in waypp \subseteq WxTxN$

waypoint schedule: battle group $g$ must be at location $n$ at time $t$

### 2. Parameters [Units]

| | |
|---|---|
| $berths_p$ | berths at port $p$ [berths] |
| $burnDFMc_c$ | capacity of burnable fuel tank for CLF ship $c$ [barrels] |
| $burnDFMs_s$ | capacity of burnable fuel tank for shuttle $s$ [barrels] |
| $burnDFMw_w$ | capacity of burnable fuel tank for warship $w$ [barrels] |
| $burnSafetyc_c$ | percentage of $burnDFMc_c$ below which CLF ship $c$ incurs a penalty [percentage] |
| $burnSafetys_s$ | percentage of $burnDFMs_s$ below which shuttle $s$ incurs a penalty [percentage] |
| $burnSafetyw_w$ | percentage of $burnDFMw_w$ below which warship $w$ incurs a penalty [percentage] |
| $capDFMc_c$ | capacity of deliverable fuel tank for CLF ship $c$ [barrels] |
| $capDFMs_s$ | capacity of deliverable fuel tank for shuttle $s$ [barrels] |
| $\varepsilon$ | small reward for fuel transfers; intended to mitigate end-of-horizon effects [reward/barrel] |
| $FC_c$ | fuel burn per time period by CLF ship $c$ [barrels] |
| $FS_s$ | fuel burn per time period by shuttle $s$ [barrels] |
| $FW_w$ | fuel burn per time period by warship $w$ [barrels] |
| $inportc_c$ | time periods required for CLF ship $c$ to remain in port on each port visit |
| $inports_s$ | time periods required for shuttle $s$ to remain in port on each port visit |
| $inportw_w$ | time periods required for warship $w$ to remain in port on each port visit |
| $nrpp$ | number of ships that can begin RASing per time period, for each shuttle and CLF [ships] |
| $penaltyc_c$ | per-unit fuel shortage penalty for CLF ship $c$ [penalty/barrel] |
| $penaltys_s$ | per-unit fuel shortage penalty for shuttle $s$ [penalty/barrel] |
| $penaltyw_w$ | per-unit fuel shortage penalty for warship $w$ [penalty/barrel] |
| $reward$ | reward for on-station time [reward/(ship*period)] |
| $safetyDFMc_c$ | percentage of $capDFMc_c$ below which CLF ship $c$ incurs a penalty [percentage] |
| $safetyDFMs_s$ | percentage of $capDFMs_s$ below which shuttle $s$ incurs a penalty [percentage] |
| $simult\_c$ | number of shuttles that can simultaneously RAS from a single CLF [ships] |

| | |
|---|---|
| $simult\_s$ | number of warships that can simultaneously RAS from a single shuttle [ships] |
| $TC_{c,i,j}$ | time periods required for CLF ship $c$ to transit from location $i$ to location $j$ [periods] |
| $TS_{s,i,j}$ | time periods required for shuttle $s$ to transit from location $i$ to location $j$ [periods] |
| $TW_{w,i,j}$ | time periods required for warship $w$ to transit from location $i$ to location $j$ [periods] |
| $TR\_S_s$ | time periods required to RAS shuttle $s$ [periods] |
| $TR\_W_w$ | time periods required to RAS warship $w$ [periods] |

### 3. Decision Variables

#### *a. Binary Decision Variables*

| | |
|---|---|
| $FDIPc^t_{c,p}$ | 1 if CLF ship $c$ enters port $p$ at time $t$ [binary] |
| $FDIPs^t_{s,p}$ | 1 if shuttle $s$ enters port $p$ at time $t$ [binary] |
| $FDIPw^t_{w,p}$ | 1 if warship $w$ enters port $p$ at time $t$ [binary] |
| $LOWF^t_w$ | 1 if warship $w$'s fuel is below safety stock at time $t$ [binary] |
| $REVUc^t_{s,c,r}$ | 1 if at start time $t$ shuttle $s$ collocated with CLF ship $c$ in RAS lane $r$ long enough to fill shuttle $s$ [binary] |
| $REVUw^t_{w,s,r}$ | 1 if at start time $t$ warship $w$ is collocated with shuttle $s$ in RAS lane $r$ long enough to fill warship $w$ [binary] |
| $YC^t_{c,i,j}$ | 1 if at time $t$ CLF ship $c$ departs location $i$ bound for location $j$ [binary] |
| $YS^t_{s,i,j}$ | 1 if at time $t$ shuttle $s$ departs location $i$ bound for location $j$ [binary] |
| $YW^t_{w,i,j}$ | 1 if at time $t$ warship $w$ departs location $i$ bound for location $j$ [binary] |

#### *b. Nonnegative Decision Variables*

| | |
|---|---|
| $HOLDc^t_c$ | deliverable fuel inventory at start of time period $t$ for CLF ship $c$ [barrels] |
| $HOLDs^t_s$ | deliverable fuel inventory at start of time period $t$ for shuttle $s$ [barrels] |
| $HOLD\_INVc^t_c$ | fuel transferred from deliverable tank to burnable tank in CLF ship $c$ during time $t$ [barrels] |
| $HOLD\_INVs^t_s$ | fuel transferred from deliverable tank to burnable tank in shuttle $s$ during time $t$ [barrels] |
| $INPc^t_c$ | burnable fuel replenished in port during time period $t$ for CLF ship $c$ [barrels] |

| | |
|---|---|
| $INPs_s^t$ | burnable fuel replenished in port during time period $t$ for shuttle $s$ [barrels] |
| $INPw_w^t$ | burnable fuel replenished in port during time period $t$ for warship $w$ [barrels] |
| $INPhc_c^t$ | deliverable fuel replenished in port at time $t$ for CLF ship $c$ [barrels] |
| $INPhs_s^t$ | deliverable fuel replenished in port at time $t$ for shuttle $s$ [barrels] |
| $RAS\_burn\_s_{s,c}^t$ | burnable fuel transferred to shuttle $s$ from CLF $c$ at time $t$ [barrels] |
| $RAS\_hold\_s_{s,c}^t$ | deliverable fuel transferred to shuttle $s$ from CLF $c$ at time $t$ [barrels] |
| $RASw_{w,s}^t$ | fuel transferred to warship $w$ from shuttle $s$ at time $t$ [barrels] |
| $SHORTBURNc_c^t$ | barrels below safety stock of burnable fuel at time period $t$ for CLF ship $c$ [barrels] |
| $SHORTBURNs_s^t$ | barrels below safety stock of burnable fuel at time period $t$ for shuttle $s$ [barrels] |
| $SHORTBURNw_w^t$ | barrels below safety stock of burnable fuel at time period $t$ for warship $w$ [barrels] |
| $SHORTc_c^t$ | barrels below safety stock of deliverable fuel at time period $t$ for CLF ship $c$ [barrels] |
| $SHORTs_s^t$ | barrels below safety stock of deliverable fuel at time period $t$ for shuttle $s$ [barrels] |

### c. *Free Variables*

| | |
|---|---|
| $INVc_c^t$ | burnable fuel inventory at start of time period $t$ for CLF ship $c$ [barrels] |
| $INVs_s^t$ | burnable fuel inventory at start of time period $t$ for shuttle $s$ [barrels] |
| $INVw_w^t$ | burnable fuel inventory at start of time period $t$ for warship $w$ [barrels] |

## 4. Formulation

$$
\begin{aligned}
Max & \sum_{t,w,(n,f)\in aw} reward * YW_{w,n,f}^t - \sum_{w,t} penaltyw_w * SHORTBURNw_w^t \\
& - \sum_{s,t} penaltys_s * \left( SHORTBURNs_s^t + SHORTs_s^t \right) \\
& - \sum_{c,t} penaltyc_c * \left( SHORTBURNc_c^t + SHORTc_c^t \right) \\
& + \varepsilon * \sum_{t\in D,s} \left( \sum_w RASw_{w,s}^t + \sum_c \left( RAS\_burn\_s_{s,c}^t + RAS\_hold\_s_{s,c}^t \right) \right) \\
& + \varepsilon * \sum_t \left( \sum_w INPw_w^t + \sum_c \left( INPc_c^t + INPhc_c^t \right) + \sum_s \left( INPs_s^t + INPhs_s^t \right) \right)
\end{aligned}
\tag{1}
$$

s.t. $$\sum_{j:(n,j)\in aw} YW_{w,n,j}^{t} = \sum_{t',i:(t',t,w,i,n)\in dW} YW_{w,i,n}^{t'}$$

$$\forall w,n,t:t>1;\ \exists i,j:(i,n)\in aw \text{ and } (n,j)\in aw \qquad (2)$$

$$\sum_{j:(n,j)\in as} YS_{s,n,j}^{t} = \sum_{t',i:(t',t,s,i,n)\in dS} YS_{s,i,n}^{t'}$$

$$\forall s,n,t:t>1;\ \exists i,j:(i,n)\in as \text{ and } (n,j)\in as \qquad (3)$$

$$\sum_{j:(n,j)\in ac} YC_{c,n,j}^{t} = \sum_{t',i:(t',t,c,i,n)\in dC} YC_{c,i,n}^{t'}$$

$$\forall c,n,t:t>1;\ \exists i,j:(i,n)\in ac \text{ and } (n,j)\in aw \qquad (4)$$

$$\sum_{(n,j)\in aw} YW_{w,n,j}^{t=1} = 1 \qquad \forall w \qquad (5)$$

$$\sum_{(n,j)\in as} YS_{s,n,j}^{t=1} = 1 \qquad \forall s \qquad (6)$$

$$\sum_{(n,j)\in ac} YC_{c,n,j}^{t=1} = 1 \qquad \forall c \qquad (7)$$

$$\sum_{j:(n,j)\in aw} YW_{w,n,j}^{t=1} = 1 \qquad \forall w,n:(w,1,n)\in wayp \quad (8)$$

$$\sum_{t',j:(t',t,w,j,n)\in dW} YW_{w,j,n}^{t'} = 1 \qquad \forall (w,t,n)\in wayp:t>1 \quad (9)$$

$$\sum_{t',w,n:(t',t,w,n,p)\in dW} YW_{w,n,p}^{t'} + \sum_{t',s,n:(t',t,s,n,p)\in dS} YS_{s,n,p}^{t'} + \sum_{t',c,n:(t',t,c,n,p)\in dC} YC_{c,n,p}^{t'} \le berths_p$$

$$\forall p,t \qquad (10)$$

$$INVw_w^t = INVw_w^{t-1} + INPw_w^{t-1} - FW_w * \left(1 - \sum_{t',n,p:(t',t,w,n,p)\in dW} YW_{w,n,p}^{t'}\right) + \sum_s RASw_{w,s}^{t-1}$$

$$\forall w,t>1 \qquad (11)$$

$$INVs_s^t = INVs_s^{t-1} + HOLD\_INVs_s^{t-1} - FS_s * \left(1 - \sum_{t',n,p:(t',t,s,n,p)\in dS} YS_{s,n,p}^{t'}\right) + INPs_s^{t-1}$$

$$+\sum_c RAS\_burn\_s_{s,c}^{t-1} \qquad \forall s,t>1 \qquad (12)$$

$$INVc_c^t = INVc_c^{t-1} + HOLD\_INVc_c^{t-1} - FC_c * \left(1 - \sum_{t',n,p:(t',c,n,p)\in dC} YC_{c,n,p}^{t'}\right) + INPc_c^{t-1}$$

$$\forall c,t>1 \qquad (13)$$

$$INPw_w^t \le burnDFMw_w \sum_{t',n,p:(t',t,w,n,p)\in dW} YW_{w,n,p}^{t'} \qquad \forall w,t \qquad (14)$$

$$INPs_s^t \le burnDFMs_s \sum_{t',n,p:(t',t,s,n,p)\in dS} YS_{s,n,p}^{t'} \qquad \forall s,t \qquad (15)$$

$$INPc_c^t \le burnDFMc_c \sum_{t',n,p:(t',t,c,n,p)\in dC} YC_{c,n,p}^{t'} \qquad \forall c,t \qquad (16)$$

$$INPhs_s^t \le capDFMs_s \sum_{t',n,p:(t',t,s,n,p)\in dS} YS_{s,n,p}^{t'} \qquad \forall s,t \qquad (17)$$

$$INPhc_c^t \le capDFMc_c \sum_{t',n,p:(t',t,c,n,p)\in dC} YC_{c,n,p}^{t'} \qquad \forall c,t \qquad (18)$$

$$HOLDs_s^t = HOLDs_s^{t-1} - HOLD\_INVs_s^{t-1} + INPhs_s^{t-1} - \sum_w RASw_{w,s}^{t-1}$$

$$+\sum_c RAS\_hold\_s_{s,c}^{(t-1)} \qquad \forall s,t>1 \qquad (19)$$

$$HOLDc_c^t = HOLDc_c^{t-1} - HOLD\_INVc_c^{t-1} + INPhc_c^{t-1} - \sum_s RAS\_burn\_s_{s,c}^{t-1}$$

$$-\sum_s RAS\_hold\_s_{s,c}^{t-1} \qquad \forall c,t>1 \qquad (20)$$

$$\sum_w REVUw_{w,s,r}^t \le nrpp \qquad \forall t\in D,s,r \qquad (21)$$

$$\sum_s REVUw_{w,s,r}^t \le nrpp \qquad \forall t\in D,s,r \qquad (22)$$

$$\sum_{w,t'\in D:\, t-TR\_W_w<t'\le t} REVUw_{w,s,r}^{t'} \le simult\_s \sum_{t',n:\,(t',t,s,n,r)\in dS} YS_{s,n,r}^{t'} \qquad \forall s,r,t\in D \qquad (23)$$

$$\sum_s REVUc_{s,c,r}^t \le nrpp \qquad \forall t\in D,c,r \qquad (24)$$

$$\sum_c REVUc_{s,c,r}^t \le nrpp \qquad \forall t\in D,s,r \qquad (25)$$

$$\sum_{s,t'\in D:\, t-TR\_S_s<t'\le t} REVUc_{s,c,r}^{t'} \le simult\_c \sum_{t',n:(t',t,c,n,r)\in dC} YC_{c,n,r}^{t'} \qquad \forall c,r,t\in D \qquad (26)$$

$$REVUw_{w,s,r}^t \le \sum_{t'',n:(t'',t'w,n,r)\in dW} YW_{w,n,r}^{t''}$$

$$\forall w,s,r,t\in D,t'\in D: t\le t'<t+TR\_W_w \qquad (27)$$

$$REVUw_{w,s,r}^t \le \sum_{t'',n:(t'',t',s,n,r)\in dS} YS_{s,n,r}^{t''}$$

$$\forall w,s,r,t\in D,t'\in D: t\le t'<t+TR\_W_w \qquad (28)$$

$$REVUc_{s,c,r}^t \le \sum_{t'',n:(t'',t',s,n,r)\in dS} YS_{s,n,r}^{t''}$$

$$\forall s,c,r,t\in D,t'\in D: t\le t'<t+TR\_S_s \qquad (29)$$

$$REVUc_{s,c,r}^t \le \sum_{t'',n:(t'',t',c,n,r)\in dC} YC_{c,n,r}^{t''}$$

$$\forall s,c,r,t\in D,t'\in D: t\le t'<t+TR\_S_s \qquad (30)$$

$$RASw_{w,s}^t \le \sum_r \left(\min\left(capDFMs_s, burnDFMw_w\right) * REVUw_{w,s,r}^{t-TR\_W_w+1}\right)$$

$$\forall s,w,t\in D \qquad (31)$$

$$RAS\_burn\_s_{s,c}^t + RAS\_hold\_s_{s,c}^t$$

$$\leq \sum_r \left( \min\left( capDFMc_c, capDFMc_s + burnDFMs_s \right) * REVUc_{s,c,r}^{t-TR\_S_s+1} \right)$$

$$\forall c,s,t \in D \qquad (32)$$

$$SHORTBURNw_w^t \geq burnSafetyw_w * burnDFMw_w - INVw_w^t \qquad \forall w,t \qquad (33)$$

$$SHORTBURNs_s^t \geq burnSafetys_s * burnDFMs_s - INVs_s^t \qquad \forall s,t \qquad (34)$$

$$SHORTBURNc_c^t \geq burnSafetyc_c * burnDFMc_c - INVc_c^t \qquad \forall c,t \qquad (35)$$

$$SHORTs_s^t \geq safetyDFMs_s * capDFMs_s - HOLDs_s^t \qquad \forall s,t \qquad (36)$$

$$SHORTc_c^t \geq safetyDFMc_c * capDFMc_c - HOLDc_c^t \qquad \forall c,t \qquad (37)$$

$$LOWF_w^t \leq 1 - \frac{\left( INVw_w^t - safetyDFMw_w * burnDFMw_w \right)}{\left( burnDFMw_w - safetyDFMw_w * burnDFMw_w \right)}$$

$$\forall w,t \qquad (38)$$

$$YW_{w,j,n}^t \geq YW_{w',j,n}^t - LOWF_w^t$$

$$\forall w,w',t,j,n : \left( w,w' \right) \in carrier, \left( j,n \right) \in aw \qquad (39)$$

$$FDIPw_{w,p}^t = \sum_{(t',i):i\neq p,(t',t,w,i,p)\in dW} YW_{w,i,p}^{t'} \qquad \forall w,p,t : \exists i : \left( i,p \right) \in aw \quad (40)$$

$$FDIPs_{s,p}^t = \sum_{(t',i):i\neq p,(t',t,s,i,p)\in dS} YS_{s,i,p}^{t'} \qquad \forall s,p,t : \exists i : \left( i,p \right) \in as \quad (41)$$

$$FDIPc_{c,p}^t = \sum_{(t',i):i\neq p,(t',t,c,i,p)\in dC} YC_{c,i,p}^{t'} \qquad \forall c,p,t : \exists i : \left( i,p \right) \in ac \quad (42)$$

$$YW_{w,p,p}^{t'} \geq FDIPw_{w,p}^t$$

$$\forall w,p,t,t' : t < t' < t + inportw_w,\ \exists i : \left( i,p \right) \in aw \qquad (43)$$

$$YS_{s,p,p}^{t'} \geq FDIPs_{s,p}^t$$

$$\forall s,p,t,t' : t < t' < t + inports_s,\ \exists i : \left( i,p \right) \in as \qquad (44)$$

$$YC_{c,p,p}^{t'} \geq FDIPc_{c,p}^t$$

$$\forall c,p,t,t' : t < t' < t + inportc_c,\ \exists i : \left( i,p \right) \in ac \qquad (45)$$

$$YW_{w,i,j}^t \in \{0,1\} \qquad \forall t,w,i,j \qquad (46)$$

$$YS_{s,i,j}^t \in \{0,1\} \qquad \forall t,s,i,j \qquad (47)$$

$$YC_{c,i,j}^t \in \{0,1\} \qquad \forall t,c,i,j \qquad (48)$$

$$REVUw_{w,s,r}^t \in \{0,1\} \qquad \forall t,w,s,r \qquad (49)$$

$$REVUc_{s,c,r}^t \in \{0,1\} \qquad \forall t,s,c,r \qquad (50)$$

$$LOWF_w^t \in \{0,1\} \qquad \forall w,t \qquad (51)$$

$$FDIPw_{w,p}^t \in \{0,1\} \qquad \forall w,p,t \qquad (52)$$

$$FDIPs_{s,p}^t \in \{0,1\} \qquad \forall s,p,t \qquad (53)$$

$$FDIPc_{c,p}^t \in \{0,1\} \qquad \forall c,p,t \qquad (54)$$

$$0 \le HOLDs_s^t \le capDFMs_s \qquad \forall t,s \qquad (55)$$
$$0 \le HOLDc_c^t \le capDFMc_c \qquad \forall t,c \qquad (56)$$
$$0 \le HOLD\_INVs_s^t \le burnDFMs_s \qquad \forall t,s \qquad (57)$$
$$0 \le HOLD\_INVc_c^t \le burnDFMc_c \qquad \forall t,c \qquad (58)$$
$$0 \le RASw_{w,s}^t \le burnDFMw_w \qquad \forall t,w,s \qquad (59)$$
$$0 \le RAS\_burn\_s_{s,c}^t \le burnDFMs_s \qquad \forall t,s,c \qquad (60)$$
$$0 \le RAS\_hold\_s_{s,c}^t \le capDFMs_s \qquad \forall t,s,c \qquad (61)$$
$$0 \le INPw_w^t \le burnDFMw_w \qquad \forall t,w \qquad (62)$$
$$0 \le INPs_s^t \le burnDFMs_s \qquad \forall t,s \qquad (63)$$
$$0 \le INPc_c^t \le burnDFMc_c \qquad \forall t,c \qquad (64)$$
$$0 \le INPhs_s^t \le capDFMs_s \qquad \forall t,s \qquad (65)$$
$$0 \le INPhc_c^t \le capDFMc_c \qquad \forall t,c \qquad (66)$$
$$0 \le SHORTBURNw_w^t \le burnSafetyw_w * burnDFMw_w \qquad \forall t,w \qquad (67)$$
$$0 \le SHORTBURNs_s^t \le burnSafetys_s * burnDFMs_s \qquad \forall t,s \qquad (68)$$
$$0 \le SHORTBURNc_c^t \le burnSafetyc_c * burnDFMc_c \qquad \forall t,c \qquad (69)$$
$$0 \le SHORTs_s^t \le safetyDFMs_s * capDFMs_s \qquad \forall t,s \qquad (70)$$
$$0 \le SHORTc_c^t \le safetyDFMc_c * capDFMc_c \qquad \forall t,c \qquad (71)$$
$$INVw_w^t \le burnDFMw_w \qquad \forall t,w \qquad (72)$$
$$INVs_s^t \le burnDFMs_s \qquad \forall t,s \qquad (73)$$
$$INVc_c^t \le burnDFMc_c \qquad \forall t,c \qquad (74)$$

## 5. Discussion

The objective function (1) rewards hours spent on-station and penalizes any fuel shortages. It also includes a small reward for all fuel transfers; this reward helps to mitigate end-of-horizon effects in which ships' inventories are depleted. Constraint sets (2), (3) and (4) require that each warship, shuttle and CLF ship, respectively, must leave a node in a period if and only if it entered node in the same period; in other words, these constraints enforce balance of flow in the ship routing network. Constraint sets (5), (6) and (7) require that each ship begin in a single location. Constraint set (8) ensures that each warship starts at its initial waypoint, if one is given. Constraint set (9) ensures that warships visit their assigned waypoints in all subsequent time periods. Constraint set (10) ensures that the number of ships visiting a port in any time period does not exceed that port's available berths. Constraint sets (11), (12) and (13) calculate the burnable fuel inventory for warships, shuttles, and CLFs, respectively, based on each ship's prior inventory, current consumption and any internal transfers, RAS transfers and port transfers that occur. Constraint sets (14), (15), (16), (17) and (18) require that each ship be located at a port node in order to take on burnable or deliverable fuel from a port. Constraint sets (19) and (20) calculate shuttle and CLF deliverable fuel inventories, respectively, based on each ship's prior inventory and any internal transfers, RAS transfers and port transfers that occur. Constraint sets (21), (22), (24) and (25) limit the number of RAS events that can be initiated at each ship in a single time period, while constraint sets (23) and (26) limit the total number of RAS events ongoing in a single time period for each shuttle and CLF. Constraint sets (27), (28), (29) and (30) ensure that all relevant ships are present at a RAS lane in order for a RAS event to occur. For instance, in order for a shuttle to replenish a warship, both the shuttle and the warship must be located at the same RAS lane during the time periods in which the RAS event is to occur, and likewise if a CLF is to replenish a shuttle. Constraint sets (31) and (32) ensure that fuel is only transferred between ships if the ships have successfully rendezvoused according to the binary *REVUw* and *REVUc* decision variables set in constraint sets (27), (28), (29) and (30). Constraint sets (33), (34) and (35) calculate burnable fuel shortages, while constraint sets (36) and (37) calculate deliverable fuel shortages. Constraint set (38) determines the value of a binary decision that indicates whether a warship's burnable fuel level is below its safety fuel level; this decision variable is used in constraint set (39) to allow the ship to depart from its battle group if it is low on fuel, and otherwise to require it to remain with its carrier. (If a battle group does not contain a carrier, an "imaginary ship" can be defined to serve this role. It is unadvisable to designate a different ship as the carrier, as this ship may run low on fuel but will never be able to separate from the battle group unless the remaining ships are also low on fuel.) Constraint sets (40), (41) and (42) determine the value of a binary decision variable indicating whether each warship, shuttle and CLF ship, respectively, begins a port visit in period $t$. Following the beginning of a port visit, constraint sets (43), (44) and (45) require that each ship to remain in port for its required number of time periods. Constraint sets (46) to (74) define decision variable domains and bounds.

## C. SCENARIO DEVELOPMENT

We exercise DL-RASM to analyze the transportation and throughput of liquid commodities to deployed vessels as a function of: 1) the type of ship within the network, 2) the operations being conducted by the ship, and 3) the duration of those operations. Our notional, unclassified scenario is based on naval operations in the 7th Fleet AOR. This AOR is important due to its proximity to the South China Sea and the highly contested Spratly Islands as well as numerous U.S. allies (Morse, 2008). As Morse so accurately stated:

> This chain of geographic features is important to the surrounding nations due to its location along the world's second busiest international sea lane, the abundance of natural gas, oil and other resources, and the desire for nations surrounding the islands to increase their claims of territorial seas and archipelagic waters…many of the nations in the region are trying to control the resources in the Spratly Islands as well as the main trade route through which oil from the Middle East and Africa is delivered. (2008)

A representation of the status of claims and disputed territory of the Spratly Islands with some minor surrounding geography is given in Figure 4.

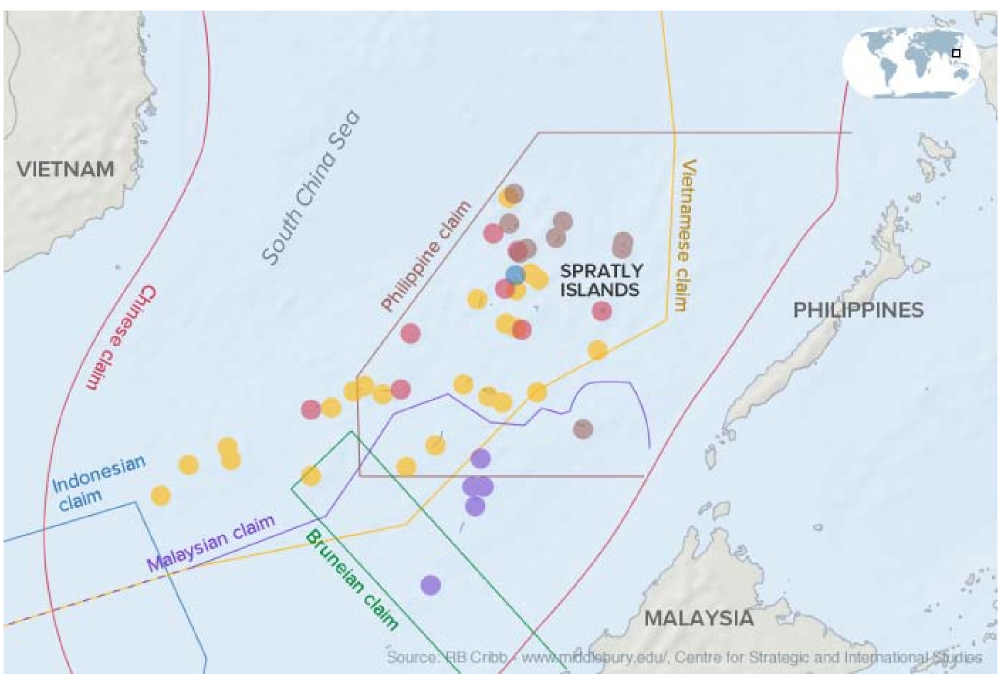



Figure 4. Contested Spratly Islands claims and surrounding geography (from Campbell, 2014)

In our scenario, tensions have increased with country red (representing the aggressor), thus driving us to evaluate a dual RAS lane logistic support method.

Our supply network contains 26 nodes, of which three are ARL nodes, seven are FOS nodes, seven are FRL nodes, three are ITP nodes and six are port nodes. This network is depicted in Figures 5–8; Figure 5 is overlain with our notional threat environment.

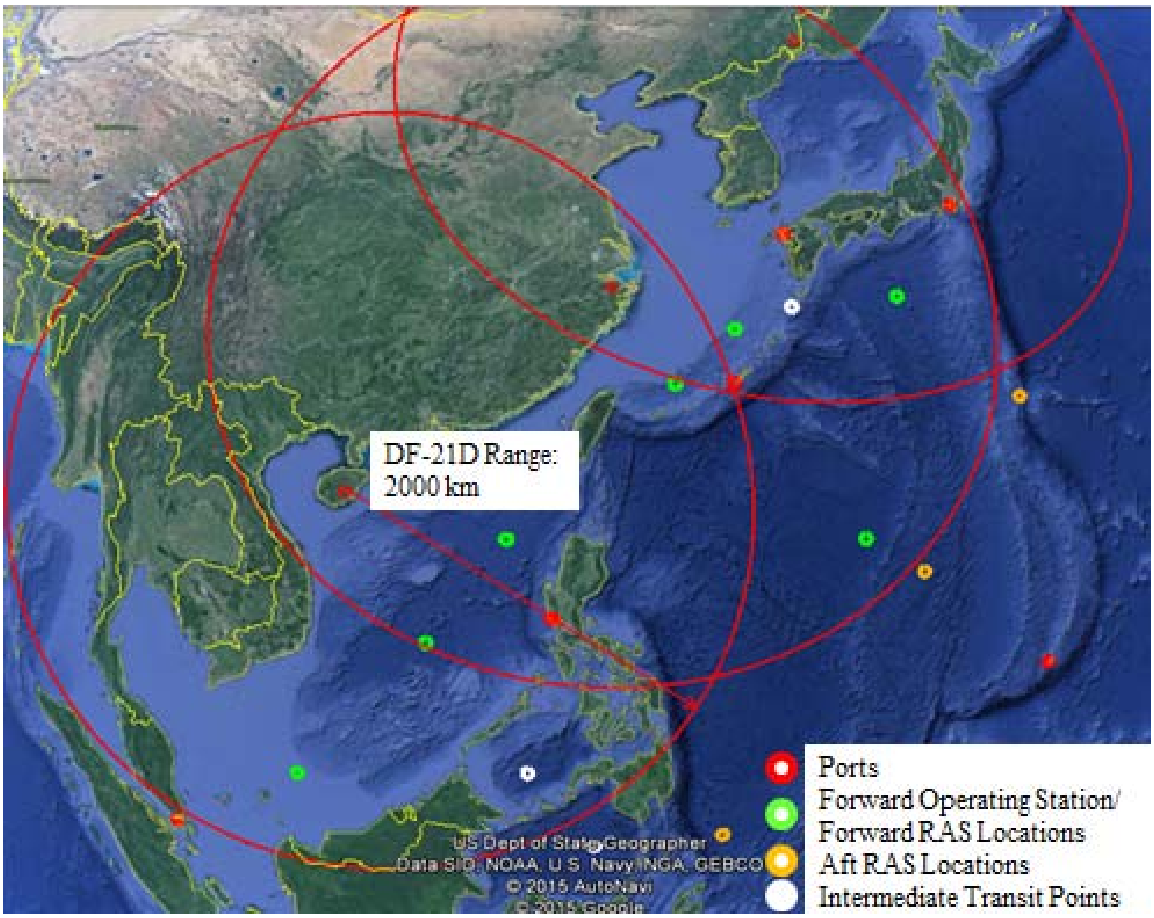



Figure 5. 7th Fleet network nodes and A2AD threat area

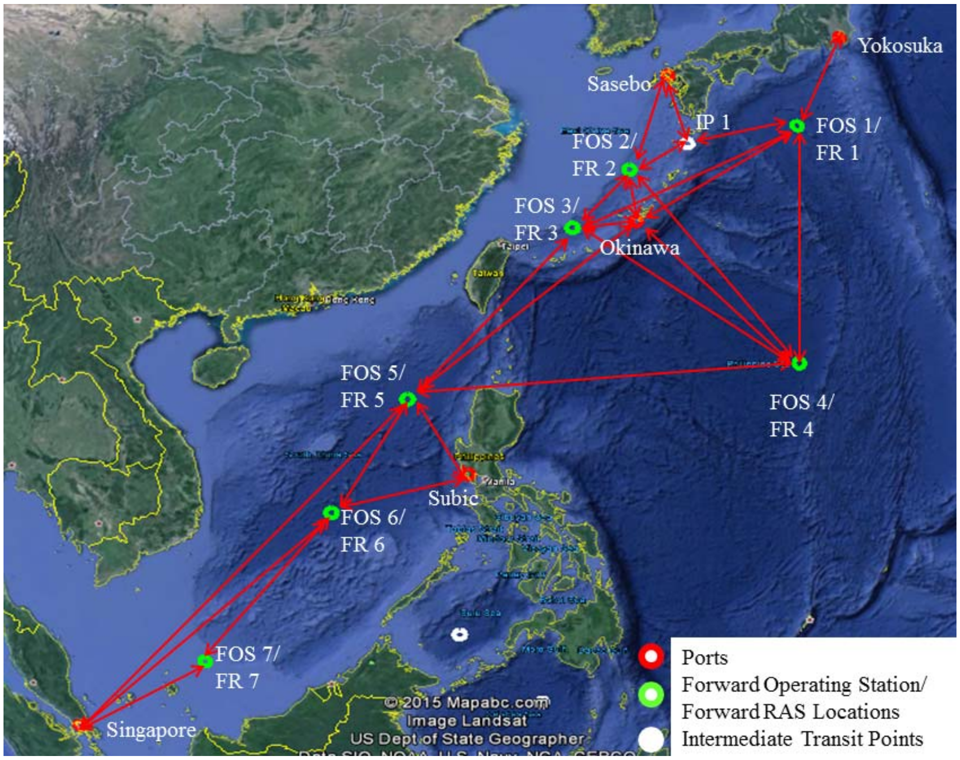



Figure 6. Warship node and arc network

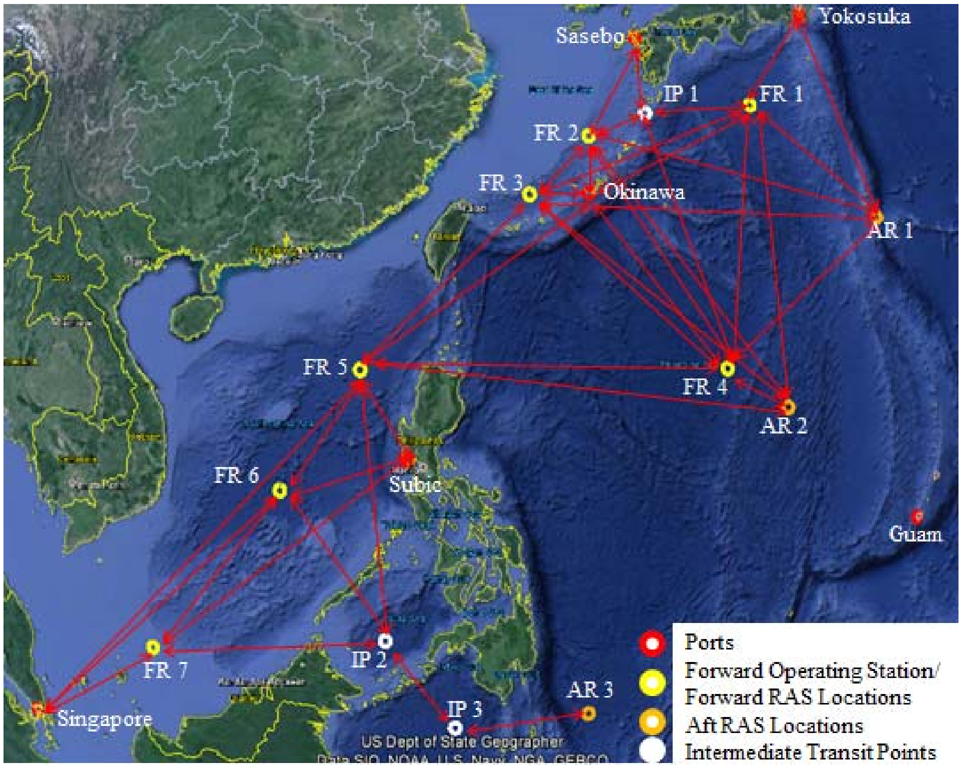



Figure 7. Shuttle node and arc network

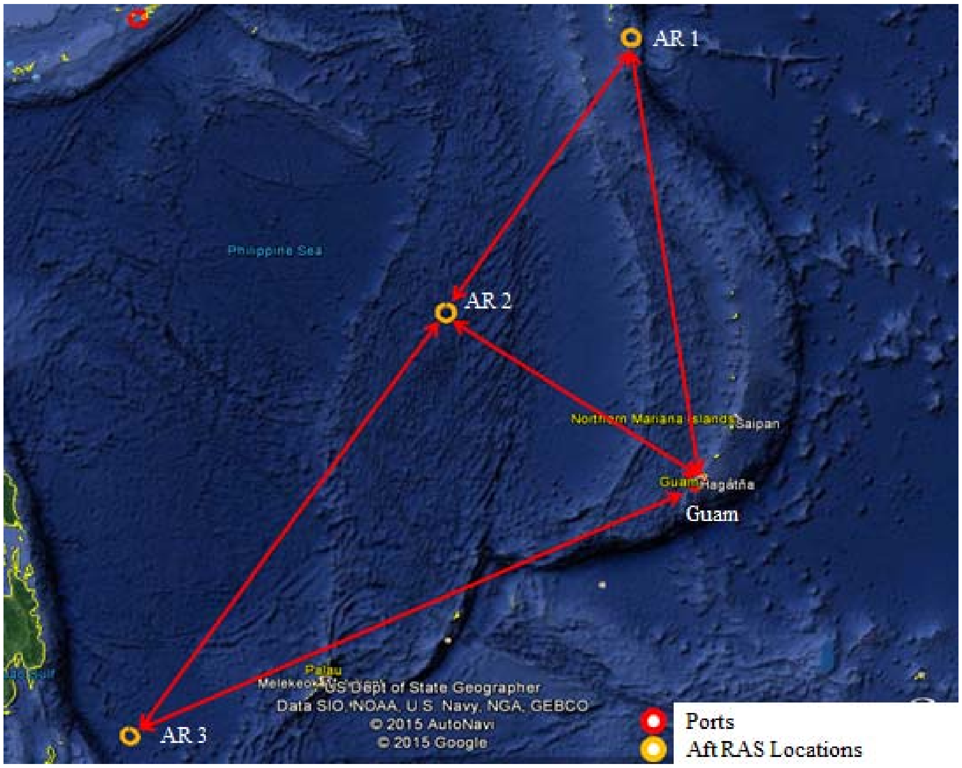



Figure 8. CLF node and arc network

### 1. Assumptions

Given this network structure, data requirements for the implemented scenario include the duration of the planning horizon, the number of hours per time period and the number of daylight hours per day available for RAS events during sustained peacetime operations. For each warship, shuttle and CLF ship, daily consumption factors for fuel, transit speeds, safety fuel levels and required days in port, are required. Finally, for each CTF/CRUDES SAG, a group composition and a waypoint schedule are required. We make the following assumptions in developing this data:

- The CLF fleet consists of only T-AO and T-AKE class ships (one each), as the future of the T-AOE is uncertain. This also represents the typical CLF support package assigned to a deployed CTF/CRUDES SAG.
- All warships begin the scenario with fuel at 85% of capacity, and all shuttle and CLF ships begin the scenario at 80% capacity for both burnable and deliverable fuel. This represents a fleet already performing sustained operations.

- All warships and CLF ships transit through the network at 15 knots (kts). This induces the requirement for a moderate but substantial fuel consumption rate to initiate and maintain a commodity demand.
- We consider four distinct shuttle speeds in our scenarios. This allows for sensitivity analysis on impact of shuttle speed and ability to support the deployed CTF/CRUDES SAG.
- We also vary shuttle deliverable fuel capacity between four distinct levels. This allows for sensitivity analysis on impact of shuttle capacity and ability to support the deployed CTF/CRUDES SAG.
- Warships, shuttles and CLF ships occupy nodes as shown in Figures 6, 7 and 8.

### 2. Fleet Composition

Afloat combat forces consist of two battle groups: one CTF and one CRUDES SAG. The CTF consists of one CVN, two guided missile cruisers (CGs), and three guided missile destroyers (DDGs), while the CRUDES SAG consists of two CGs and three DDGs. Our logistics assets consist of one T-AO and one T-AKE, and we vary the number of shuttles from three to eight in our sensitivity analysis.

### 3. CTF/CRUDES SAG Schedule

Both battle groups initialize in their assigned operating area and execute "show of force" operations reflected in their waypoint schedules, shown in Table 3. The time periods represent the first time period the battle group is required to be on station for the assigned exercise to commence in the following time periods.

Table 3. Waypoint schedule for battle groups

| Time Period (*t*) | Battle Group (*g*) | Location (*i*) |
|---|---|---|
| 1-47 | CTF | FOS_4 |
| 1-35 | CRUDES SAG | FOS_5 |
| 42-71 | CRUDES SAG | FOS_6 |
| 60-100 | CTF | FOS_2 |
| 78 | CRUDES SAG | FOS_5 |
| 90-155 | CRUDES SAG | FOS_3 |
| 103 | CTF | FOS_3 |
| 120-140 | CTF | FOS_5 |
| 148-180 | CTF | FOS_6 |
| 168-180 | CRUDES SAG | FOS_1 |

### 4. Planning Factors

The logistics planning factors used in our scenarios come directly from CLF Planner (2008), and were retrieved from NWP 4-01.2 (CNO, 2007) and a more recent study by CNA Corporation (Trickey, 2014). We use these factors to determine the daily consumption rates, fuel capacities, required days in port and speed for the warships, shuttles and CLF ships.

#### *a. Warships*

The data used to produce our warship planning factors are shown in Figures 9, 10 and 11. We utilize the values circled in red; the values circled or highlighted in yellow were also considered but not adopted. In all cases, the values used were consistent with the most conservative or current values employed. Conservative values were adopted for fuel consumption rates and were taken from the CLF Planner planning factors, while current values were adopted for capacities and were taken from the

CNA study. The planning factors for the warships actually applied to the scenarios for DL-RASM are depicted in Table 4.

CLF

**Ship Planning Factors**

| ShipType | Commodity | Capacity | InTransit | AtAnchor | Docked | OnStation | Training | PreAssault | Assault | Sustain |
|---|---|---|---|---|---|---|---|---|---|---|
| CVN | DFM | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| CVN | JP5 | 74,642 | 3000 | 0 | 0 | 4000 | 4000 | 3000 | 5000 | 4000 |
| CVN | STOR | 1,710 | 53 | 53 | 53 | 53 | 53 | 53 | 53 | 53 |
| CVN | ORDN | 1,765 | 2.5 | 0 | 0 | 5 | 20 | 15 | 150 | 100 |
| CG | DFM | 15,032 | 757 | 151.4 | 151.4 | 605.6 | 757 | 1429 | 757 | 757 |
| CG | JP5 | 475 | 8.5 | 0 | 0 | 17 | 25.5 | 17 | 39 | 25.5 |
| CG | STOR | 68 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| CG | ORDN | 94 | 0.075 | 0 | 0 | 0.15 | 0.6 | 0.6 | 5 | 3 |
| DDG | DFM | 10,518 | 646 | 129.2 | 129.2 | 516.8 | 646 | 1200 | 646 | 646 |
| DDG | JP5 | 475 | 8.5 | 0 | 0 | 17 | 25.5 | 17 | 34 | 25.5 |
| DDG | STOR | 55 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| DDG | ORDN | 48 | 0.05 | 0 | 0 | 0.1 | 0.4 | 0.4 | 3 | 2 |

Figure 9. CLF Planner planning factors for the fuel capacity and burn rates of the warships (from Brown & Carlyle, 2008)

| Ship | Mission area name | Arrival day | Quantity | Priority | Departure day | Ship number | Mission Area | DFM capacity (bbls) | Assault DFM consumption (bbls/0.1 day) | Pre-assault DFM Consumption (bbls/0.1 day) | Ordnance capacity (stons) | Assault ordnance consumption rate (stons/0.1 day) | Pre-assault ordnance consumption rate (stons/0.1 day) | Ship | Starting DFM (bbls) | Starting ordnance (stons) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AMPH01 LHD | AMPHIB | 0 | 1 | 1 | 150 | 1 | 2 | 43,091 | 107 | 200 | 391 | 3.3 | 0.66 | 1 | 38,782 | 352 |
| AMPH02 LPD-17 | AMPHIB | 0 | 1 | 2 | 150 | 2 | 2 | 23,750 | 107 | 114 | 513 | 0.6 | 0.12 | 2 | 21,375 | 462 |
| AMPH03 LSD | AMPHIB | 0 | 1 | 3 | 150 | 3 | 2 | 19,150 | 35 | 73 | 35 | 0.2 | 0.04 | 3 | 17,235 | 32 |
| CG01 | CG | 0 | 1 | 2 | 150 | 4 | 3 | 15,032 | 76 | 143 | 94 | 0.5 | 0.1 | 4 | 13,529 | 85 |
| CG02 | CG | 0 | 1 | 3 | 150 | 5 | 3 | 15,032 | 76 | 143 | 94 | 0.5 | 0.1 | 5 | 13,529 | 75 |
| CG03 | CG | 0 | 1 | 2 | 150 | 6 | 3 | 15,032 | 76 | 143 | 94 | 0.5 | 0.1 | 6 | 13,529 | 66 |
| CG04 | CG | 0 | 1 | 3 | 150 | 7 | 3 | 15,032 | 76 | 143 | 94 | 0.5 | 0.1 | 7 | 13,529 | 56 |
| CVN01 | CVN | 0 | 1 | 3 | 150 | 8 | 4 | 1 | 0 | 0 | 1,765 | 15 | 3 | 8 | 1 | 1,589 |
| CVN02 | CVN | 0 | 1 | 3 | 150 | 9 | 4 | 1 | 0 | 0 | 1,765 | 15 | 3 | 9 | 1 | 1,589 |
| DDG01 | DDG | 0 | 1 | 2 | 150 | 10 | 5 | 10,518 | 65 | 120 | 48 | 0.3 | 0.06 | 10 | 9,466 | 43 |
| DDG02 | DDG | 0 | 1 | 3 | 150 | 11 | 5 | 10,518 | 65 | 120 | 48 | 0.3 | 0.06 | 11 | 9,466 | 38 |
| DDG03 | DDG | 0 | 1 | 2 | 150 | 12 | 5 | 10,518 | 65 | 120 | 48 | 0.3 | 0.06 | 12 | 9,466 | 34 |

Figure 10. CNA Corporation: *Navy Logistics Resiliency Model Description* fuel capacity and burn rate warship planning factors (from Trickey, 2014)

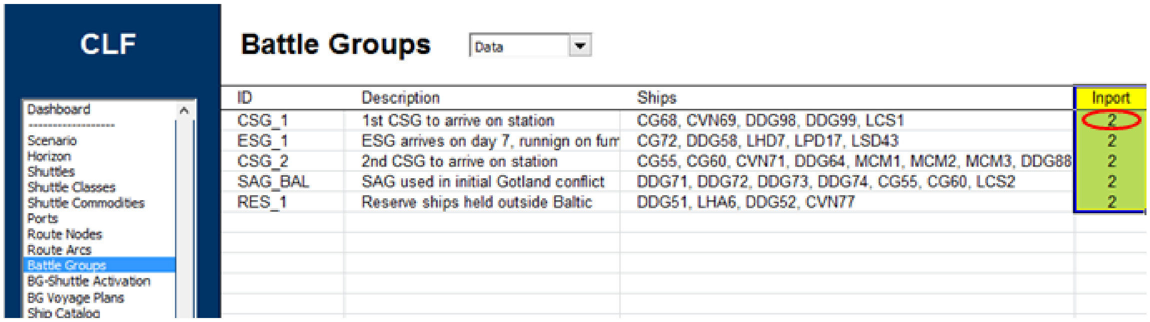



Figure 11. CLF Planner planning factor for minimum in-port duration (from Brown & Carlyle, 2008)

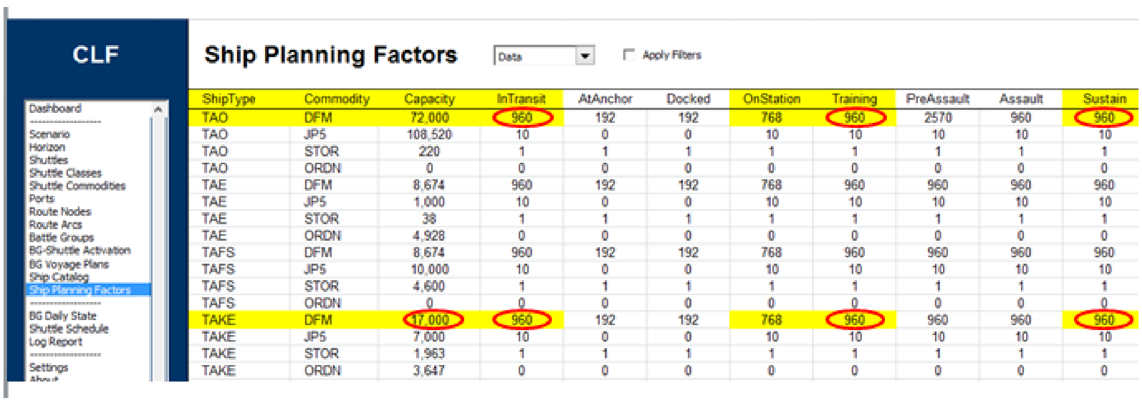
Table 4. DL-RASM warship planning factors (after Brown & Carlyle, 2008; Trickey, 2014)

| ID ($w$) | *Bg* (Battle Group) | $Speed_w$ (kts) | $Inport_w$ (days) | $burnDFM_w$ (bbls) | $safetyDFM_w$ (portion of $burnDFMw_w$) | Fuel Burn (%/day) |
|---|---|---|---|---|---|---|
| DDG_1 | CTF | 15 | 2 | 10518 | 0.7 | 6.14 |
| DDG_2 | CTF | 15 | 2 | 10518 | 0.7 | 6.14 |
| DDG_3 | CTF | 15 | 2 | 10518 | 0.7 | 6.14 |
| DDG_4 | CRUDES SAG | 15 | 2 | 10518 | 0.7 | 6.14 |
| DDG_5 | CRUDES SAG | 15 | 2 | 10518 | 0.7 | 6.14 |
| DDG_6 | CRUDES SAG | 15 | 2 | 10518 | 0.7 | 6.14 |
| CG_1 | CTF | 15 | 2 | 15032 | 0.7 | 5.04 |
| CG_2 | CTF | 15 | 2 | 15032 | 0.7 | 5.04 |
| CG_3 | CRUDES SAG | 15 | 2 | 15032 | 0.7 | 5.04 |
| CG_4 | CRUDES SAG | 15 | 2 | 15032 | 0.7 | 5.04 |
| CVN_1 | CTF | 15 | 3 | 74642 | 0.7 | 5.36 |

The *bg,* and *safetyDFM* planning factors are based on the author's observations during multiple assignments to CVN's and DDG's. Note that we calculate $FW_w$ based on the fuel burn given in Table 4.

### *b. CLF*

In Tables 12, 13 and 14 can be found the data used to produce the CLF planning factors. As with the warship planning factors, red circles indicate the values used, while the values circled or highlighted in yellow were considered but not adopted. Again, actual values were used where possible, and conservative values were used otherwise. Conservative values were adopted for fuel consumption rates, and current values were adopted for capacities. Our planning factors for CLF ships are shown in Table 5.




| ShipType | Commodity | Capacity | InTransit | AtAnchor | Docked | OnStation | Training | PreAssault | Assault | Sustain |
|---|---|---|---|---|---|---|---|---|---|---|
| TAO | DFM | 72,000 | 960 | 192 | 192 | 768 | 960 | 2570 | 960 | 960 |
| TAO | JP5 | 108,520 | 10 | 0 | 0 | 10 | 10 | 10 | 10 | 10 |
| TAO | STOR | 220 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| TAO | ORDN | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| TAE | DFM | 8,674 | 960 | 192 | 192 | 768 | 960 | 960 | 960 | 960 |
| TAE | JP5 | 1,000 | 10 | 0 | 0 | 10 | 10 | 10 | 10 | 10 |
| TAE | STOR | 38 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| TAE | ORDN | 4,928 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| TAFS | DFM | 8,674 | 960 | 192 | 192 | 768 | 960 | 960 | 960 | 960 |
| TAFS | JP5 | 10,000 | 10 | 0 | 0 | 10 | 10 | 10 | 10 | 10 |
| TAFS | STOR | 4,600 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| TAFS | ORDN | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| TAKE | DFM | 17,000 | 960 | 192 | 192 | 768 | 960 | 960 | 960 | 960 |
| TAKE | JP5 | 7,000 | 10 | 0 | 0 | 10 | 10 | 10 | 10 | 10 |
| TAKE | STOR | 1,963 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| TAKE | ORDN | 3,647 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Figure 12. CLF Planner planning factors for the CLF ships (from Brown & Carlyle, 2008)

| Ship type name | Ship number | Ship type | Station or Shuttle | Arrival day | Quantity | Priority | Ship number | Speed | Ship's fuel DFM capacity (bbls) | DFM consumption (bbls/day) | DFM capacity (bbls) | JP5 capacity (bbls) | Stores capacity (stons) | Ordnance capacity (stons) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TAO | 1 | 1 | 1 | 0 | 1 | 2 | 1 | 17 | 14,453 | 505 | 90,000 | 90,000 | 220 | 0 |
| TAO | 2 | 1 | 1 | 0 | 1 | 1 | 2 | 17 | 14,453 | 505 | 90,000 | 90,000 | 220 | 0 |
| TAO | 3 | 1 | 1 | 0 | 1 | 3 | 3 | 17 | 14,453 | 505 | 90,000 | 90,000 | 220 | 0 |
| TAO | 4 | 1 | 2 | 0 | 1 | 2 | 4 | 17 | 14,453 | 505 | 90,000 | 90,000 | 220 | 0 |
| TAOE | 5 | 3 | 2 | 0 | 1 | 2 | 5 | 26 | 31,750 | 914 | 62,400 | 93,600 | 952 | 2,016 |
| TAKE | 6 | 2 | 2 | 0 | 1 | 2 | 6 | 18 | 31,494 | 593 | 17,000 | 7,000 | 1,300 | 4,900 |
| TAKE | 7 | 2 | 1 | 0 | 1 | 2 | 7 | 18 | 31,494 | 593 | 17,000 | 7,000 | 1,300 | 4,900 |
| TAKE | 8 | 2 | 1 | 0 | 1 | 3 | 8 | 18 | 31,494 | 593 | 17,000 | 7,000 | 1,300 | 4,900 |
| TAKE | 9 | 2 | 1 | 30 | 1 | 2 | 9 | 18 | 31,494 | 593 | 17,000 | 7,000 | 1,300 | 4,900 |
| TAKE | 10 | 2 | 1 | 30 | 1 | 3 | 10 | 18 | 31,494 | 593 | 17,000 | 7,000 | 1,300 | 4,900 |

Figure 13. CNA Corporation: *Navy Logistics Resiliency Model Description* CLF ship planning factors (from Trickey, 2014)

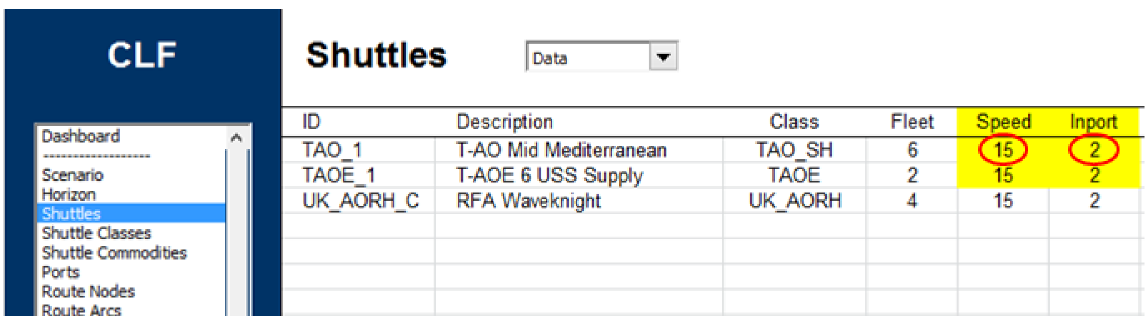



Figure 14. CLF Planner planning factor for minimum in-port duration (from Brown & Carlyle, 2008)

Table 5. DL-RASM CLF planning factors
(after Brown & Carlyle, 2008; Trickey, 2014)

| ID ($c$) | $Speed_c$ (kts) | $Inport_c$ (days) | $burnDFM_c$ (bbls) | $capDFM_c$ (bbls) | $burnsafetyDFM_c$ (portion of $burnDFMc_c$) | $safetyDFM_c$ (portion of $capDFMc_c$) | Fuel Burn (%/day) |
|---|---|---|---|---|---|---|---|
| TAO_1 | 15 | 2 | 14453 | 90000 | 0.5 | 0.3 | 6.64 |
| TAKE_1 | 15 | 2 | 31494 | 17000 | 0.5 | 0.3 | 3.05 |

### c. *Shuttle Ships*

The shuttle ship planning factors were modeled after the planning factors for a DDG 51 class ship power plant. Assuming the shuttle design is to be smaller in dimension than the target in Figure 2 and possibly has increased speed capabilities, the DDG 51 class ship power plant provides conservative design characteristics to accomplish both goals. Table 6 is an exhibit of the planning factors for a nominal design of the shuttle ship, and in Tables 7 and 8 are shown the planning factor ranges, where applicable, for the shuttle ships. In addition to varying the planning factors, we also vary the number of shuttles available from three to eight.

Table 6. Baseline shuttle planning factors derived from DDG 51 Class power plant consumption rates (after Brown & Carlyle, 2008; Trickey, 2014)

| Nominal $Speed_s$ (kts) | $Inport_s$ (days) | $burnDFMs_s$ (bbls) | Nominal $capDFMs_s$ (bbls) | $burnsafetyDFM_s$ (portion of $burnDFMs_s$) | $safetyDFM_s$ (portion of $capDFMs_s$) | Nominal Fuel Burn (%/day) |
|---|---|---|---|---|---|---|
| 15 | 1 | 10518 | 23810 | 0.5 | 0.3 | 6.14 |

Table 7. Unclassified planning factors for sensitivity analysis pertaining to shuttle ship speed and corresponding fuel burn percentage based on DDG 51 class daily consumption planning factors (after Trickey & Grenwald, 2014)

| $Speed_s$ (kts) | Fuel Burn (%/day) |
|---|---|
| 13 | 5.4 |
| 15 | 6.14 |
| 17 | 7.2 |
| 19 | 8.5 |

Table 8. Deliverable fuel capacity levels for sensitivity analysis pertaining to shuttle ship design

| Deliverable fuel capacity (gal) | $capDFMs_s$ (bbls) |
|---|---|
| 750,000 | 17,857 |
| 1,000,000 | 23,810 |
| 1,250,000 | 29,762 |
| 1,500,000 | 35,714 |

#### *d. Ports*

We conservatively assume that two berths are available at each port; that is, at most two ships can occupy each port in each time step. Actual available berths for refueling may vary.

#### *e. Penalties and Rewards*

Our penalty and reward parameters are listed in Table 9. For simplicity, we vary penalties by ship type (i.e., warship, shuttle or CLF) but not by individual ship.

Table 9. Penalty and reward parameter values

| $reward$ (reward/ship*period) | $\varepsilon$ (reward/barrel) | $penaltyw_w$ (penalty/barrel) | $penaltys_s$ (penalty/barrel) | $penaltyc_c$ (penalty/barrel) |
|---|---|---|---|---|
| 1000 | .00001 | 1000 | 100 | 10 |

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# IV. ANALYSIS

We now exercise DL_RASM to study the performance of various shuttle configurations. In Chapter IV, Section A, we consider peacetime operations, as reflected by the parameter values described in Chapter III, Section B. In this setting, we evaluate a number of shuttle configurations in order to determine those characteristics that have the largest impact on DL-RASM's objective value. Then, in Chapter IV, Section B, we consider a wartime scenario in which the shuttles are denied port access and must refuel at the ARLs. In this setting, we again evaluate the performance of various shuttle configurations.

We consider a 30-day time horizon for each of our computational experiments. Rather than optimize over the entire 30 days simultaneously, we utilize a rolling horizon approach. In the first iteration, we optimize over a planning horizon of 20 time periods (80 operational hours). We then fix the binary decision variables for the first five time periods and expand our planning horizon by five periods. We continue this process until our planning horizon encompasses the entire 30 days. This approach allows us to reduce DL_RASM's computational burden while accurately reflecting actual operations.

Each of our design points as applied to DL-RASM was computed using a Dell, Precision T7500 computer with two Intel® Xenon® CPU E5606 @2.13GHz processors, 48 GB of RAM installed and running the Windows 7 Professional operating system. The program software used for the optimization is GAMS 24.0.1 utilizing CPLEX 12.5 solver. With these conditions our model contains approximately 111,530 constraints and 192,913 decision variables in the first iteration, of which181,874 decision variables are integer. In the last iteration of the rolling time horizon implementation, our model contains approximately 747,810 constraints and 555,831 decision variables, of which 55,640 decision variables are integer. Solution times vary by iteration but are typically in the range of 4.96 to 19.75 seconds.

## A. PEACETIME OPERATIONS

We wish to study the impact of three design parameters: speed, deliverable fuel capacity, and available number of shuttles. In order to efficiently explore this design space, we apply a three-factor custom nearly orthogonal Latin hypercube (NOLH) design of experiments (DOE). The purpose of the custom NOLH DOE is to efficiently reduce the amount of overall design points evaluated while maintaining near orthogonality across all factors and filling enough design space to determine higher order effects between the factors (Cioppa & Lucas, 2007). Our custom NOLH DOE was derived from the DesignCreatorv2 spreadsheet produced by MacCalman (2012).

The Appendix contains our design points as well as DL-RASM's optimal objective value for each design point. These results appear graphically in Figures 15, 16 and 17. In Figure 15, it appears that a speed of 19 kts produces higher optimal objective values; however, at a capacity of 1.5M gallons, all speeds perform well. Moreover, in Figure 16, we see that increasing the number of shuttles has some positive effect on the optimal objective value. But again, the 1.5M gallon deliverable fuel capacity consistently results in the higher objective values. Finally, in Figure 17, we see a direct positive impact by the increase of deliverable fuel and generally with an increase in the number of shuttles. From the graphs we are able to deduce that in all cases, regardless of speed and with little respect to the number of shuttles, a capacity of 1.5M gallons provides robust good performance. Moreover, this parameter value is determined at the time of ship construction and is not subject to perturbation in the operational environment, as speed and number of shuttles are.

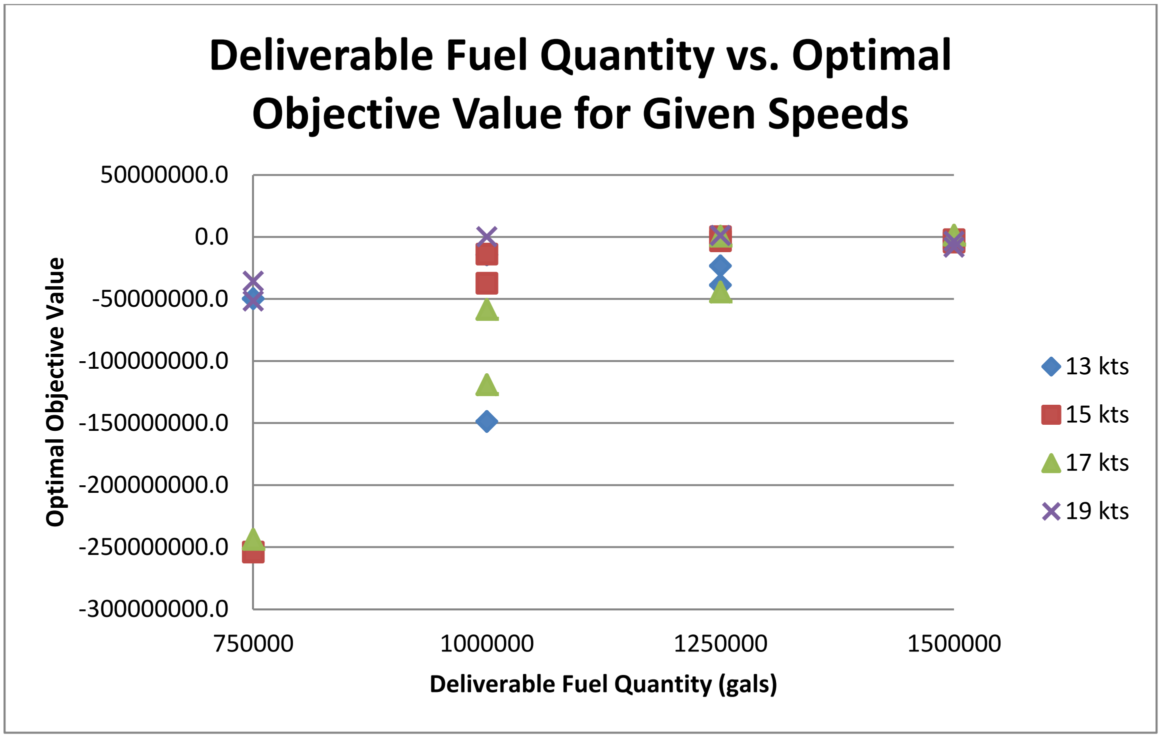


Figure 15. Optimal objective value as a function of shuttle deliverable fuel capacity and speed

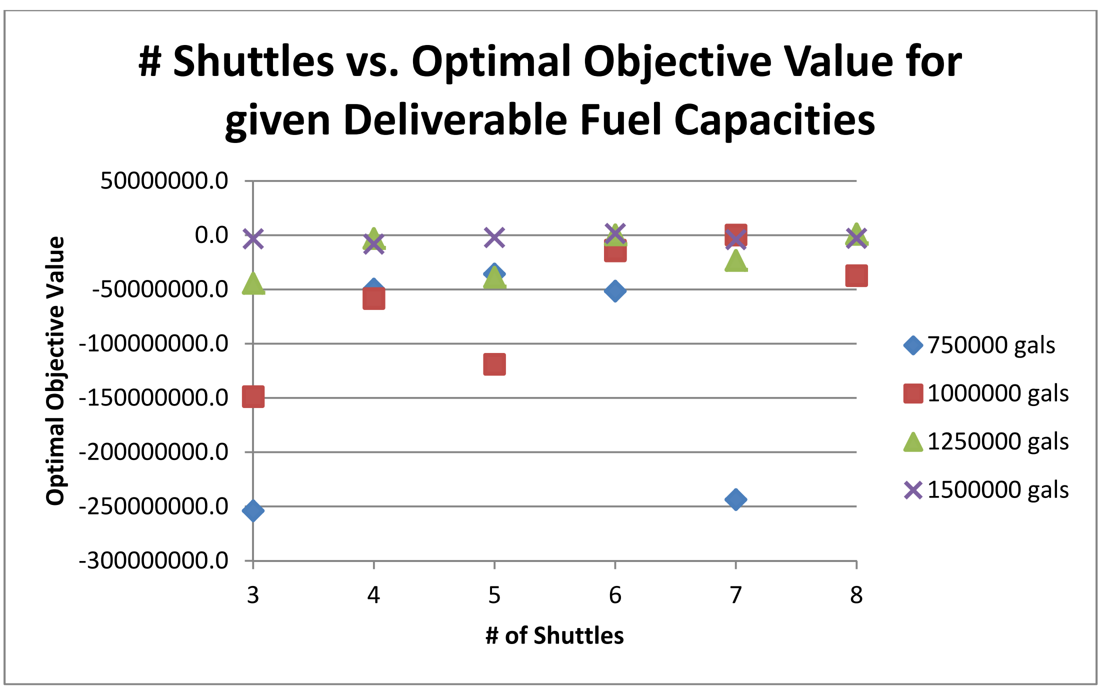


Figure 16. Optimal objective value as a function of # of shuttles and deliverable fuel capacity

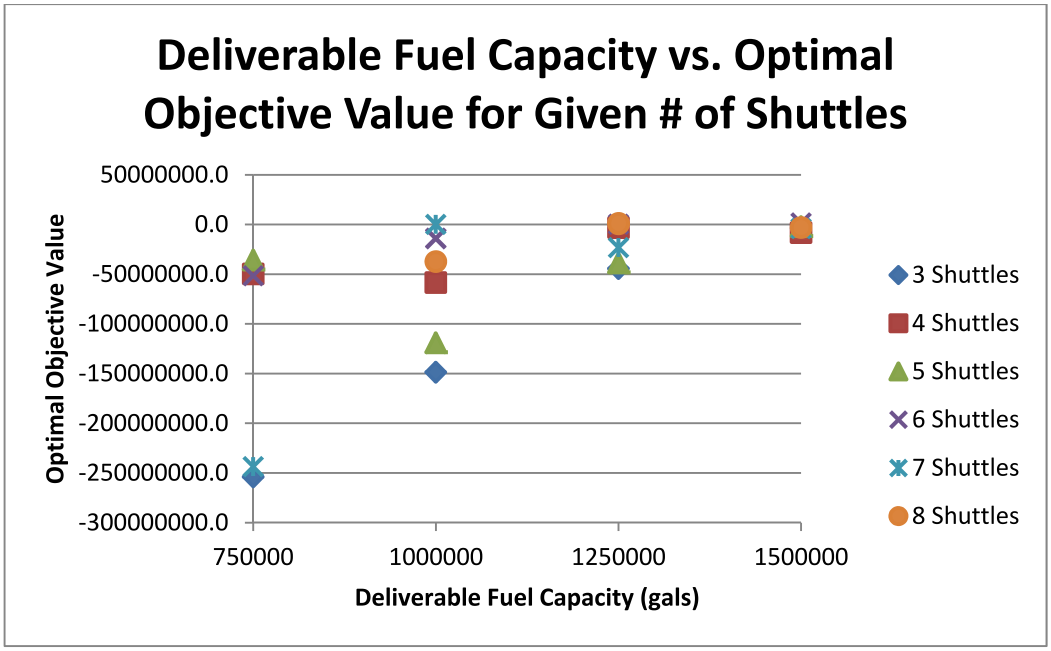


Figure 17. Optimal objective value as a function of deliverable fuel capacity and number of shuttles

We now assume a conservative speed of 15 kts and perform a more detailed sensitivity analysis on a number of shuttles, as this is a value that may change unexpectedly in a wartime scenario. We also examine the impact of shuttle capacity in more detail.

### 1. Three Shuttles, 750,000-Gallon Deliverable Fuel Capacity

We first consider a “pessimistic” scenario in which we only have three shuttles, each with a deliverable fuel capacity of 750,000 gallons. Fuel inventories of the warships and shuttles in this scenario are shown in Figures 18, 19 and 20. As indicated in the figures, both warships and shuttles encounter fuel levels below safety stock in many time periods. This represents an undesirable outcome for our nominal scenario, as well as an inability to support increased demands if unforeseen adverse events were to occur.

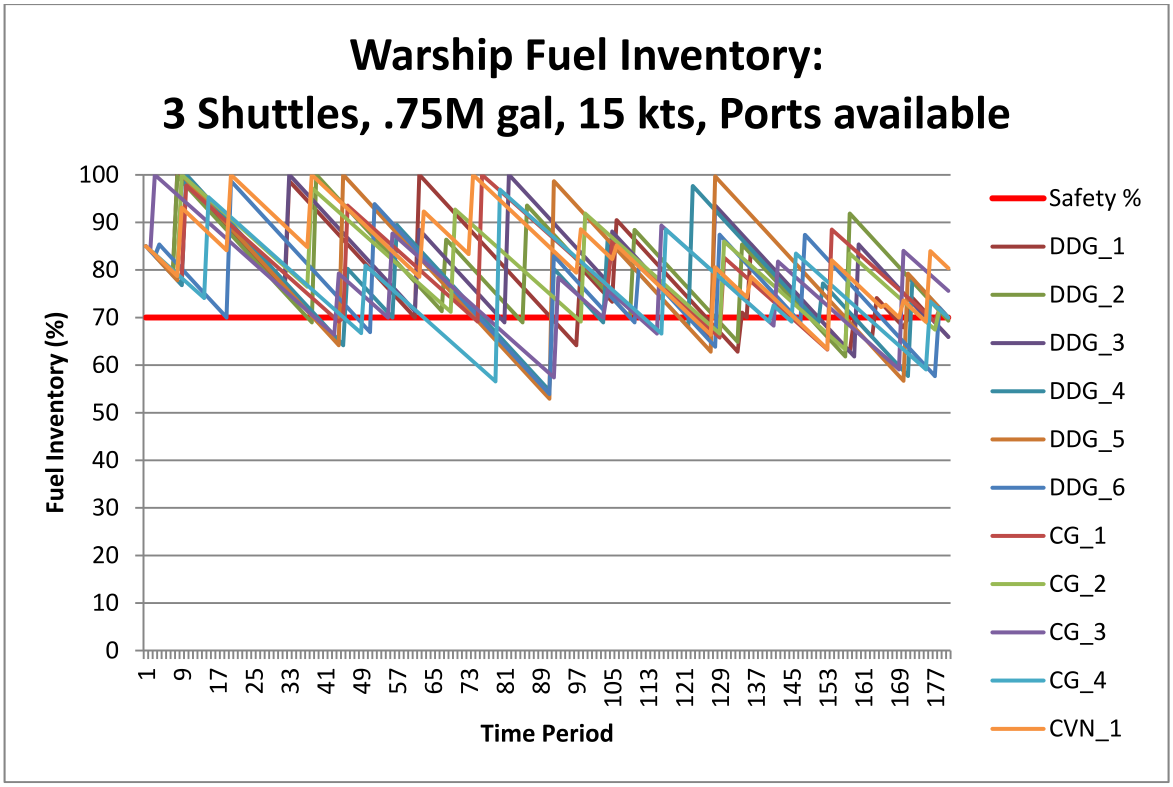


Figure 18. Warship fuel inventory levels during a 30-day time horizon utilizing three shuttles with a 750,000 gallon deliverable fuel quantity and ports available

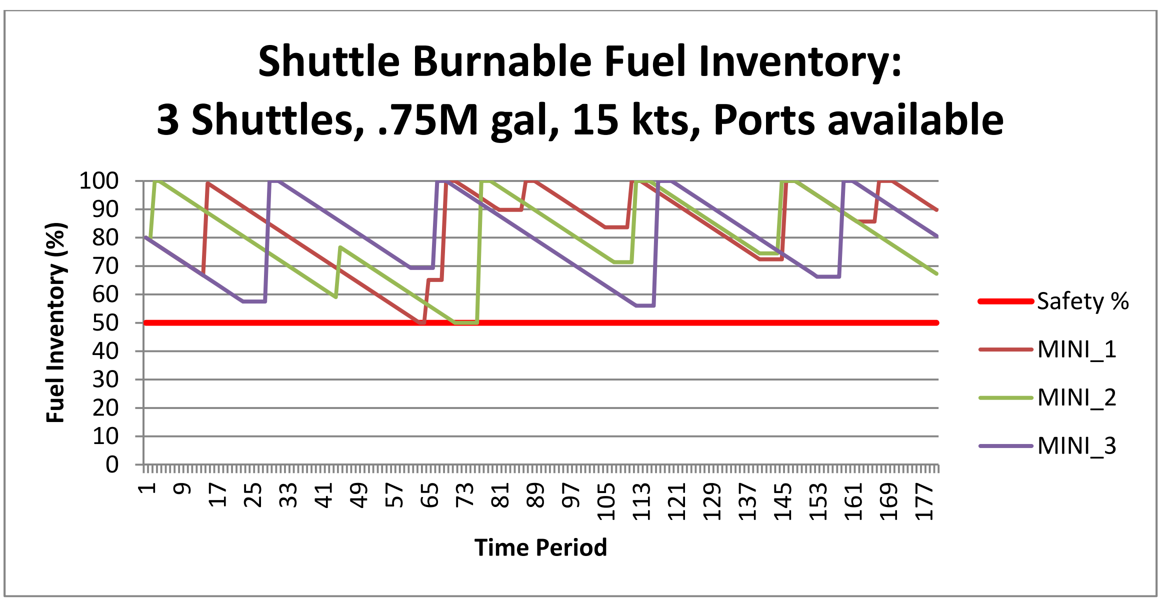


Figure 19. Shuttle burnable fuel inventory levels during a 30-day time horizon utilizing three shuttles with a 750,000 gallon deliverable fuel quantity and ports available

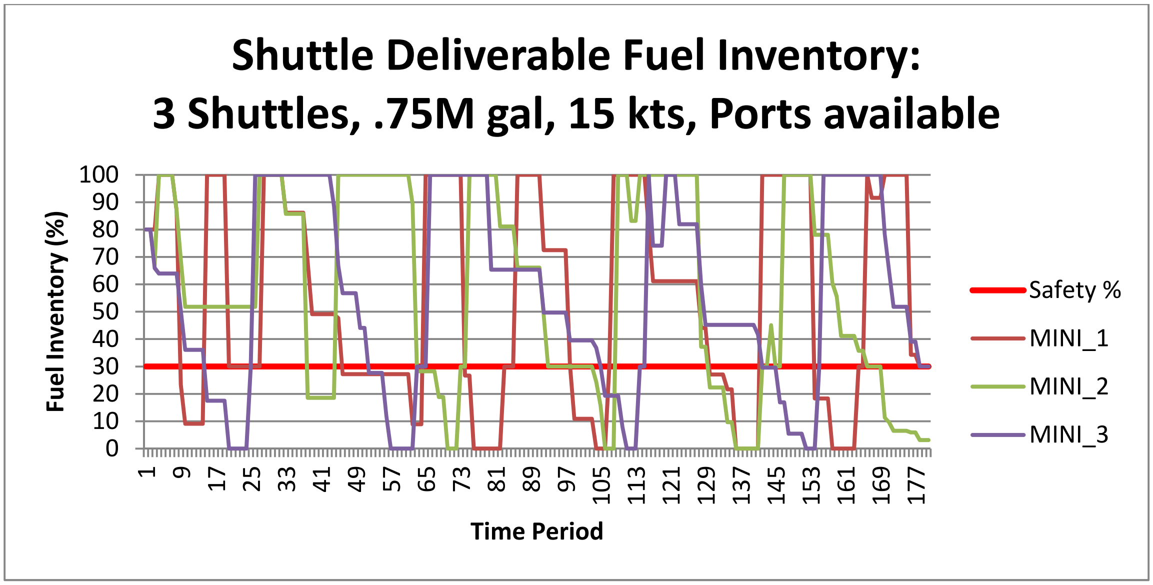


Figure 20. Shuttle deliverable fuel inventory levels during a 30-day time horizon utilizing three shuttles with a 750,000 gallon deliverable fuel quantity and ports available

Table 10 is a summary of the activities of the warships during this scenario. In particular, each warship's time spent on station (Time on FOS), transiting between locations of awaiting fuel (Transit/Wait), and time spent receiving fuel (Active RAS) each as a percentage of the planning horizon are depicted. Warships do not spend time in port because their waypoint schedule does not permit it.

Table 10. Warship employment when three shuttles are available, each with a 750,000 gallon deliverable fuel capacity

| Percentage | DDG_1 | DDG_2 | DDG_3 | DDG_4 | DDG_5 | DDG_6 | CG_1 | CG_2 | CG_3 | CG_4 | CVN_1 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time on FOS | 68.9 | 67.8 | 70.0 | 74.4 | 74.4 | 73.9 | 67.8 | 69.4 | 74.4 | 73.9 | 69.4 |
| Transit/Wait Time | 25.0 | 28.3 | 25.6 | 21.1 | 22.8 | 21.1 | 27.8 | 26.7 | 21.1 | 22.2 | 23.3 |
| Active RAS | 6.1 | 3.9 | 4.4 | 4.4 | 2.8 | 5.0 | 4.4 | 3.9 | 4.4 | 3.9 | 7.2 |

Recall that a warship can only depart from its battle group if its fuel inventory falls below its prescribed safety stock level, as indicated by Equations (38) and (39). Thus, the Transit/Wait times in Table 10 reflect some situations in which an entire battle group visits a FRL so that one or more of its ships can refuel before reaching safety stock level. In this case, the entire battle group is taken off station during the duration of the RAS event.

### 2. Six Shuttles, 1.5M-Gallon Deliverable Fuel Capacity

We now consider a more optimistic scenario in which six shuttles are available, each with a deliverable fuel capacity of 1.5M gallons. The fuel quantities of the warships and shuttles in this scenario are depicted in Figures 21, 22 and 23. Note that excursions below safety stock are quite minimal at this design point.

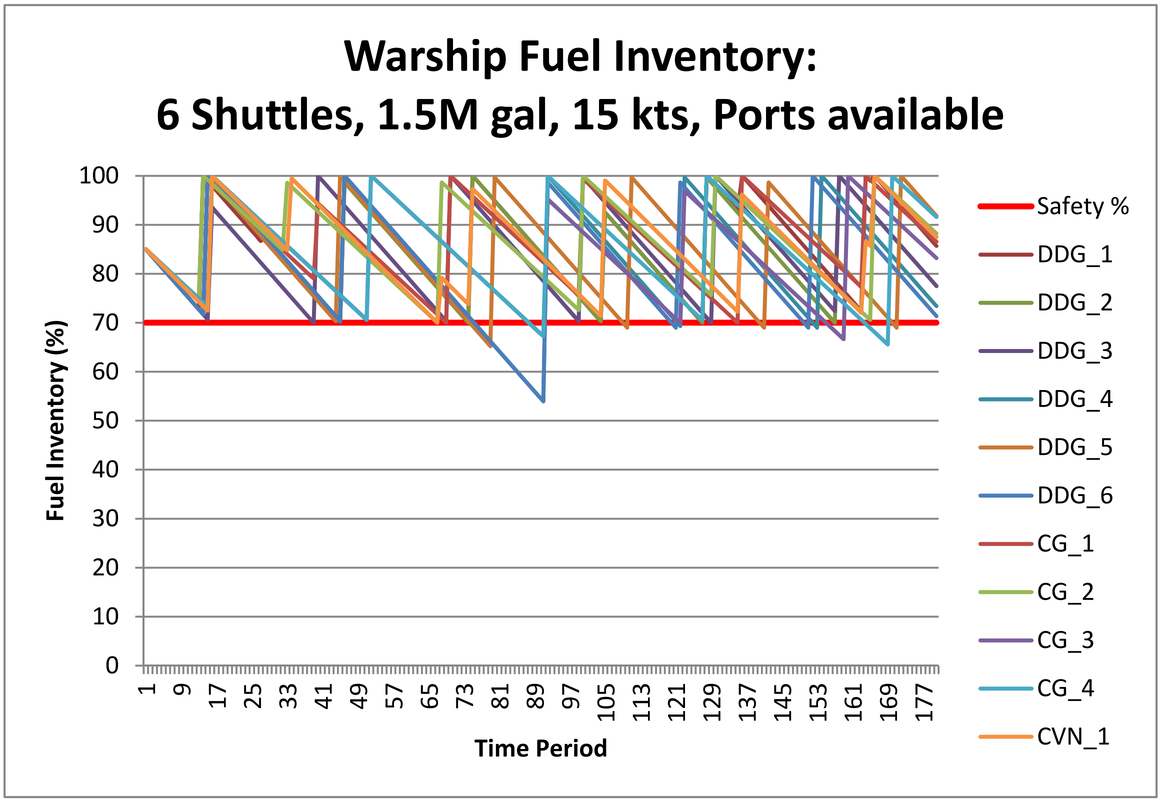


Figure 21. Warship fuel inventory levels during a 30-day time horizon utilizing six shuttles with a 1.5 M-gallon deliverable fuel quantity and ports available

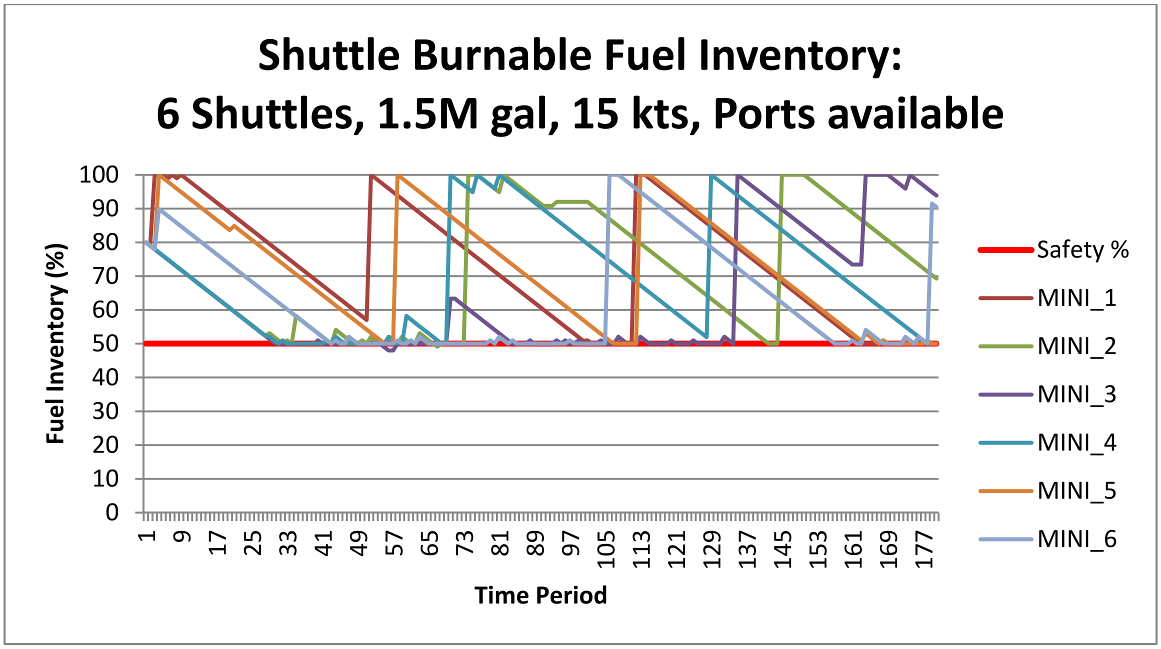


Figure 22. Shuttle burnable fuel inventory levels during a 30-day time horizon utilizing six shuttles with 1.5 M-gallon deliverable fuel quantity and ports available

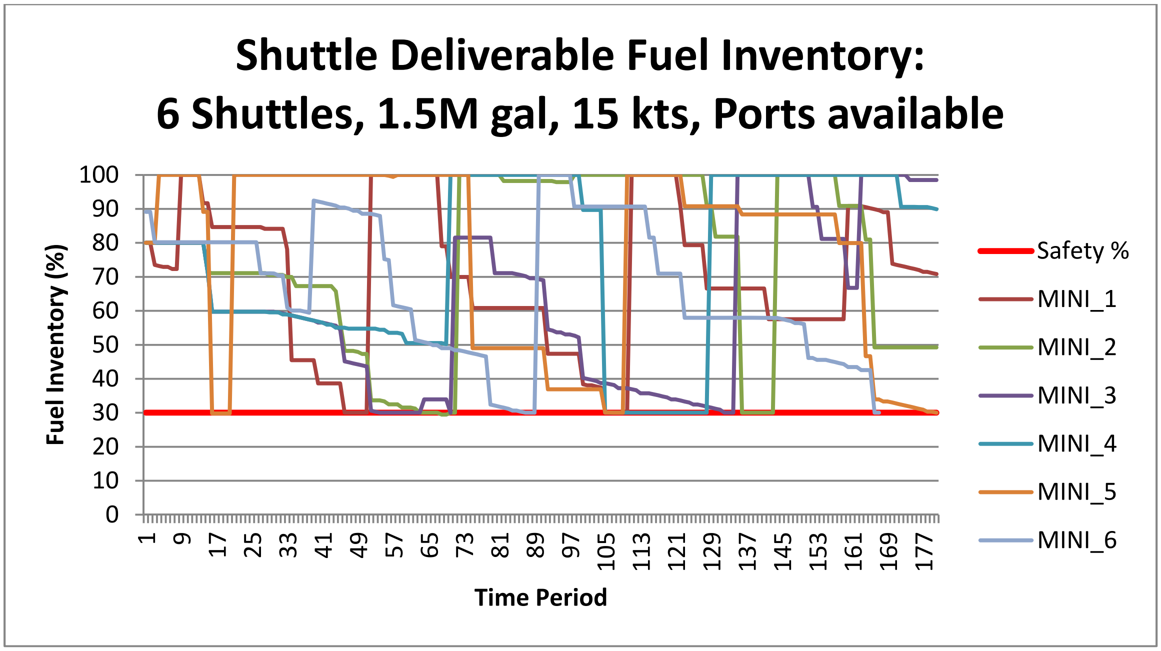


Figure 23. Shuttle deliverable fuel inventory levels during a 30-day time horizon utilizing six shuttles with 1.5 M-gallon deliverable fuel quantity and ports available

The percentage of time spent on station, transiting or waiting, and actively refueling at sea, for each warship is displayed in Table 11. Note that the 6-shuttle, 1.5M gal design point results in improved on-station times relative to the 3-shuttle, 0.75M gal design point; this improvement is quantified in Table 12.

Table 11. Warship employment when six shuttles are available, each with a 1.5 M-gallon deliverable fuel capacity

| Percentage | DDG_1 | DDG_2 | DDG_3 | DDG_4 | DDG_5 | DDG_6 | CG_1 | CG_2 | CG_3 | CG_4 | CVN_1 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time on FOS | 73.3 | 73.3 | 73.3 | 77.2 | 76.1 | 76.7 | 73.3 | 73.3 | 77.2 | 77.2 | 73.3 |
| Transit/Wait Time | 21.7 | 23.3 | 23.3 | 19.4 | 20.6 | 20.0 | 23.3 | 23.3 | 20.0 | 20.0 | 22.2 |
| Active RAS | 5.0 | 3.3 | 3.3 | 3.3 | 3.3 | 3.3 | 3.3 | 3.3 | 2.8 | 2.8 | 4.4 |

Table 12. Change in warship employment from the three-shuttle design point to the six-shuttle design point, as a percentage of the 30-day time horizon

| Percentage | DDG_1 | DDG_2 | DDG_3 | DDG_4 | DDG_5 | DDG_6 | CG_1 | CG_2 | CG_3 | CG_4 | CVN_1 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time on FOS | 4.4 | 5.6 | 3.3 | 2.8 | 1.7 | 2.8 | 5.6 | 3.9 | 2.8 | 3.3 | 3.9 |
| Transit/Wait Time | -3.3 | -5.0 | -2.2 | -1.7 | -2.2 | -1.1 | -4.4 | -3.3 | -1.1 | -2.2 | -1.1 |
| Active RAS | -1.1 | -0.6 | -1.1 | -1.1 | 0.6 | -1.7 | -1.1 | -0.6 | -1.7 | -1.1 | -2.8 |

As indicated in Table 12, we see an average increase in Time on FOS of 3.6%, equating to almost 26 hours per warship during the 30-day planning horizon for our scenario. The warships also enjoy an average decrease in Transit/Wait time of 2.5% of the 30-day horizon and a decrease in Active RAS time of 1.1% of the 30-day horizon, corresponding to a decrease of 18 hours and 8 hours per warship for these activities, respectively.

## B. WARTIME OPERATIONS: DENIED PORT ACCESS

In our peacetime scenario, we find that the shuttles make heavy use of the ports of Sasebo and Okinawa, Japan, and Subic Bay, Philippines for refueling, while only making limited use of the ARLs and CLFs. While this heavy usage of ports is completely reasonable given the distances involved, it does invite the potential for disruption due to the fact that these ports lie within the A2AD environment. Thus, we now consider a situation in which access is denied for all ports except Guam. In this situation, the shuttles must refuel at the ARLs, while the CLFs are able to refuel at Guam.

### 1. Six Shuttles, 1.5M-Gallon Deliverable Fuel Capacity

In Figures 24, 25 and 26 are depicted the fuel quantities of the warships and shuttles when six shuttles are available, each with a deliverable fuel capacity of 1.5M gallons. As indicated, this design point is no longer adequate to support warship requirements in a heightened threat environment. Because warship inventories are prioritized in the objective function, they are the least affected. However, we do see warship inventories below safety stock in a number of time periods, particularly near the end of the 30-day horizon. Moreover, the situation is worse for shuttles: we see shuttle inventories below safety stock beginning early in the 30-day horizon, and by the halfway point at least one shuttle’s inventory is below safety stock in every time period, for both burnable and deliverable fuel. In fact, we even witness shuttle burnable fuel inventories below zero, an operational impossibility that is allowed in DL-RASM only to ensure that a feasible solution exists.

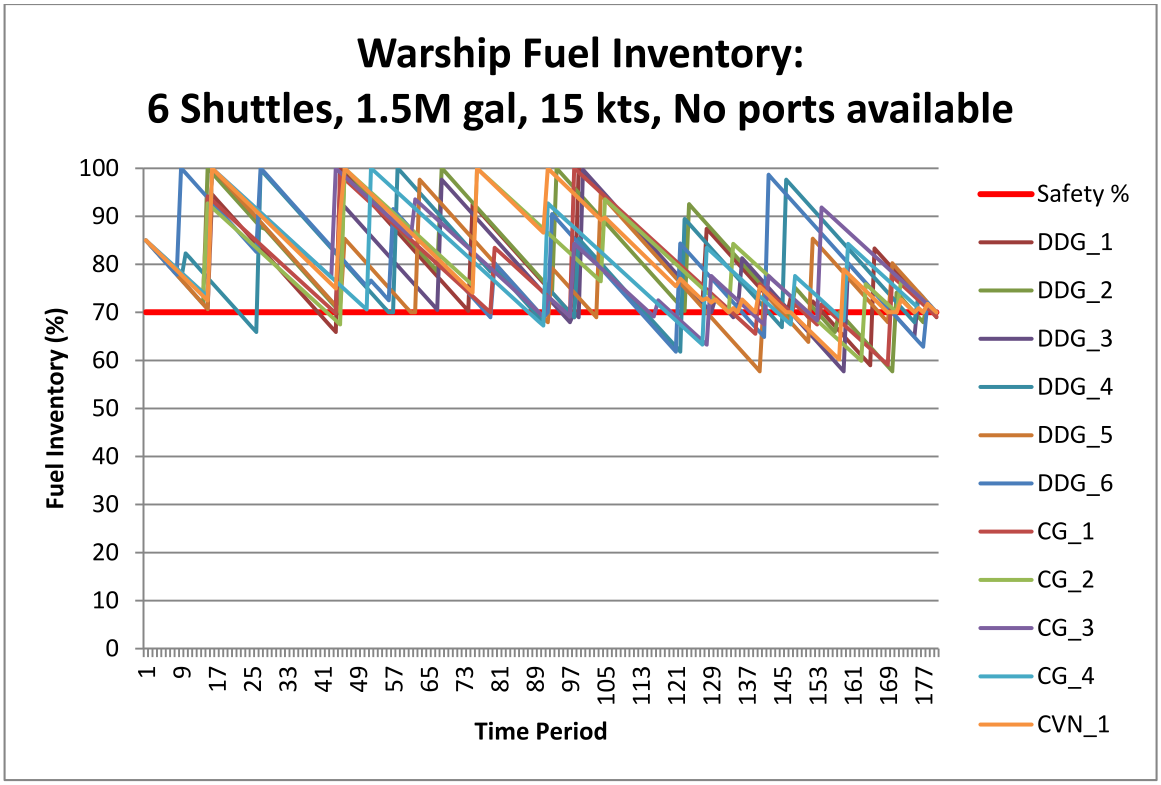


Figure 24. Warship fuel inventory levels during a 30-day time horizon utilizing six shuttles with a 1.5 M-gallon deliverable fuel quantity and no ports available

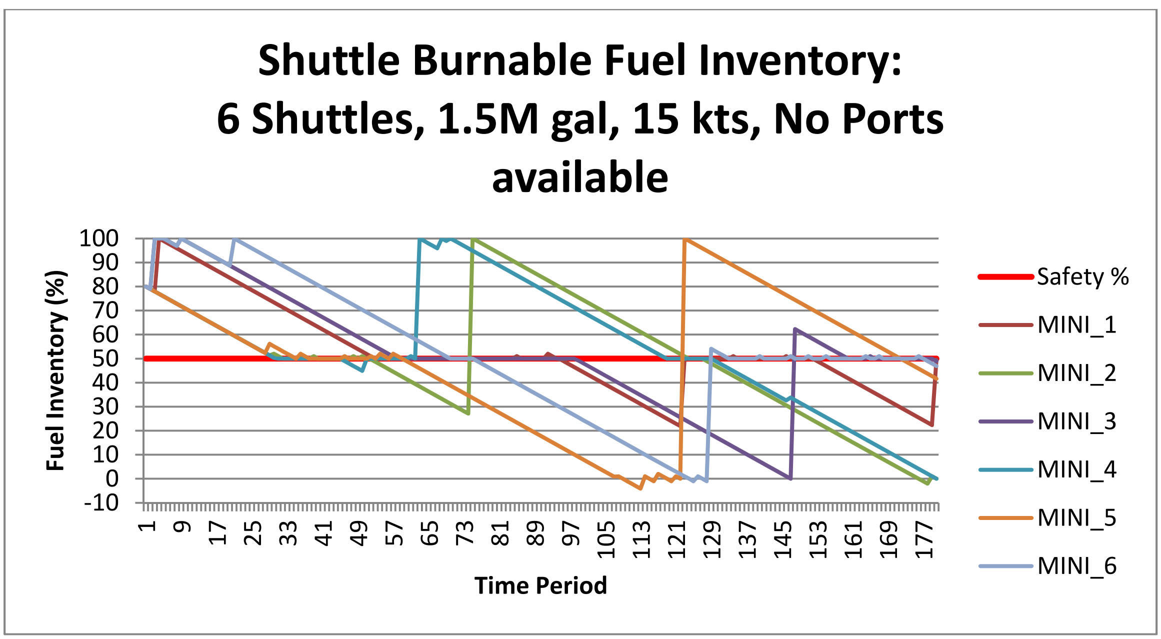


Figure 25. Shuttle burnable fuel inventory levels during a 30-day time horizon utilizing six shuttles with 1.5 M-gallon deliverable fuel quantity and no ports available

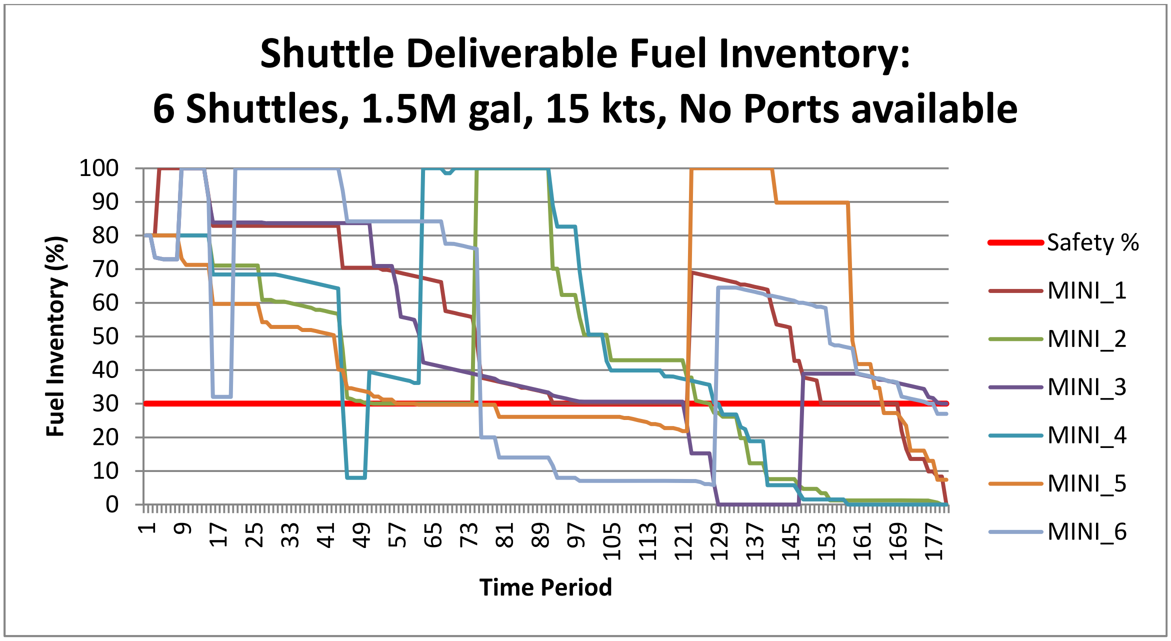


Figure 26. Shuttle deliverable fuel inventory levels during a 30-day time horizon utilizing six shuttles with 1.5 M-gallon deliverable fuel quantity and no ports available

Table 13 is the model output generated Time on FOS, Transit/Wait, and Active RAS times as a percentage of the planning horizon for this scenario.

Table 13. Warship employment as a function of percentage of time per given activity for six shuttles and 1.5 M-gallon of deliverable fuel quantity each

| Percentage | DDG_1 | DDG_2 | DDG_3 | DDG_4 | DDG_5 | DDG_6 | CG_1 | CG_2 | CG_3 | CG_4 | CVN_1 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time on FOS | 65.0 | 66.1 | 64.4 | 71.7 | 71.7 | 72.2 | 66.1 | 66.1 | 71.7 | 73.3 | 66.7 |
| Transit/Wait Time | 30.6 | 28.3 | 30.0 | 22.8 | 23.3 | 22.2 | 29.4 | 30.0 | 23.3 | 22.8 | 22.8 |
| Active RAS | 4.4 | 5.6 | 5.6 | 5.6 | 5.0 | 5.6 | 4.4 | 3.9 | 5.0 | 3.9 | 10.6 |

The change in percentages for this design point in the heightened threat environment with no ports available is found in Table 14. The results indicate an average decrease of 6.3% Time on FOS, equating to almost 45.4 hours per warship during the 30-day planning horizon. They also indicate an average increase of 4.4% Transit/Wait Time and 1.9% Active RAS time, resulting in an increase of 31.7 hours and 13.7 hours per warship for the given activity, respectively.

Table 14. Percentage of time change per given activity from the optimal design of six shuttles and 1.5 M-gallon deliverable fuel with ports available for shuttle replenishment and the optimal design in the heightened threat scenario with no ports

| Percentage | DDG_1 | DDG_2 | DDG_3 | DDG_4 | DDG_5 | DDG_6 | CG_1 | CG_2 | CG_3 | CG_4 | CVN_1 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time on FOS | -8.3 | -7.2 | -8.9 | -5.6 | -4.4 | -4.4 | -7.2 | -7.2 | -5.6 | -3.9 | -6.7 |
| Transit/Wait Time | 8.9 | 5.0 | 6.7 | 3.3 | 2.8 | 2.2 | 6.1 | 6.7 | 3.3 | 2.8 | 0.6 |
| Active RAS | -0.6 | 2.2 | 2.2 | 2.2 | 1.7 | 2.2 | 1.1 | 0.6 | 2.2 | 1.1 | 6.1 |

### 2. Eight Shuttles, 1.5M-Gallon Deliverable Fuel Capacity

To mitigate the performance degradation we observe when port access is denied, we now increase the number of available shuttles form six to eight, each with a 1.5M gallon deliverable fuel capacity. In Figures 27, 28, and 29 are displayed the warship and shuttle inventories for this design point; note the substantial decrease in time spent below safety stock, relative to the six-shuttle design point. We do see more instances of low fuel inventories toward the end of the 30-day horizon; this can result in part from the end-of-horizon effects and does not necessarily indicate an inability to sustain performance.

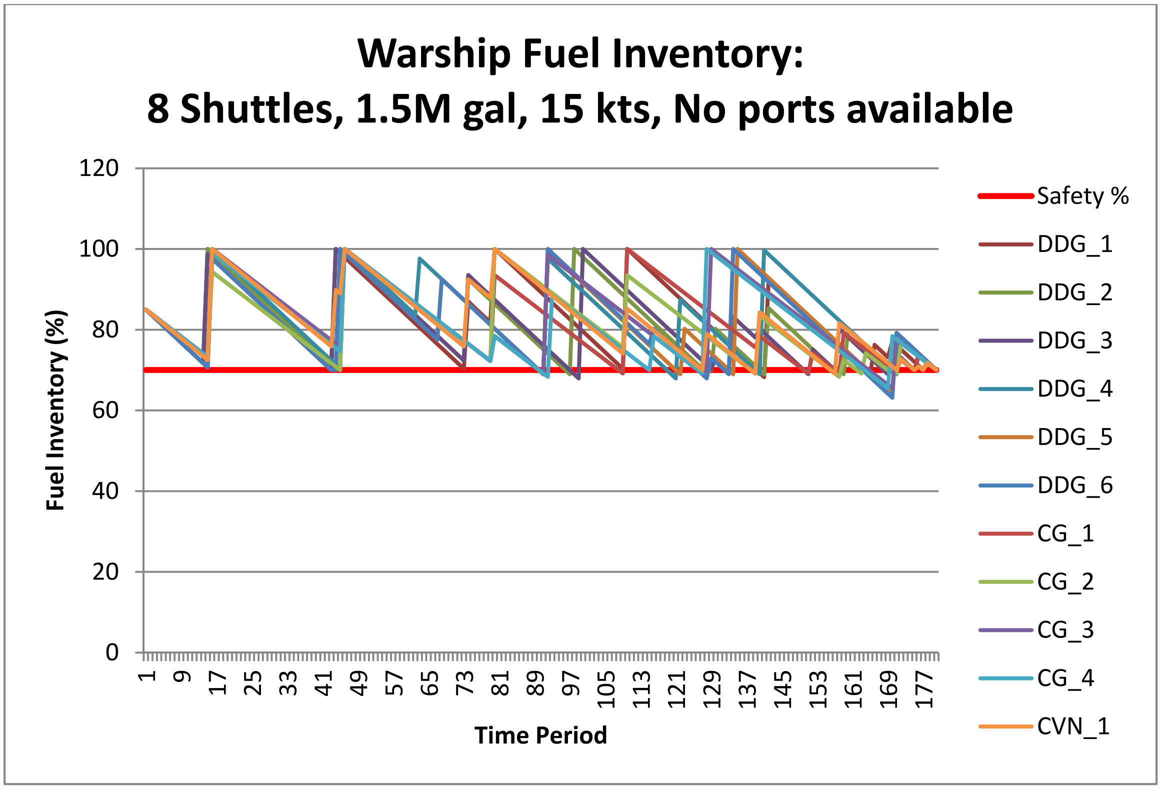


Figure 27. Warship fuel inventory levels during a 30-day time horizon utilizing eight shuttles with a 1.5 M-gallon deliverable fuel quantity and no ports available

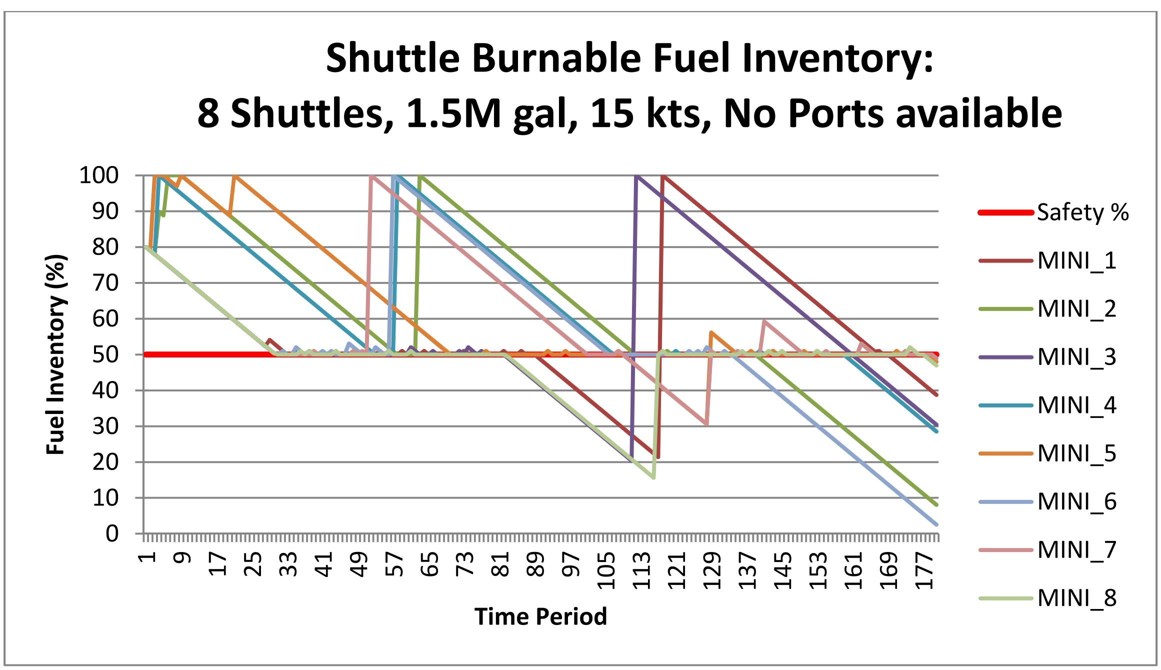


Figure 28. Shuttle burnable fuel inventory levels during a 30-day time horizon utilizing eight shuttles with 1.5 M-gallon deliverable fuel quantity no ports available

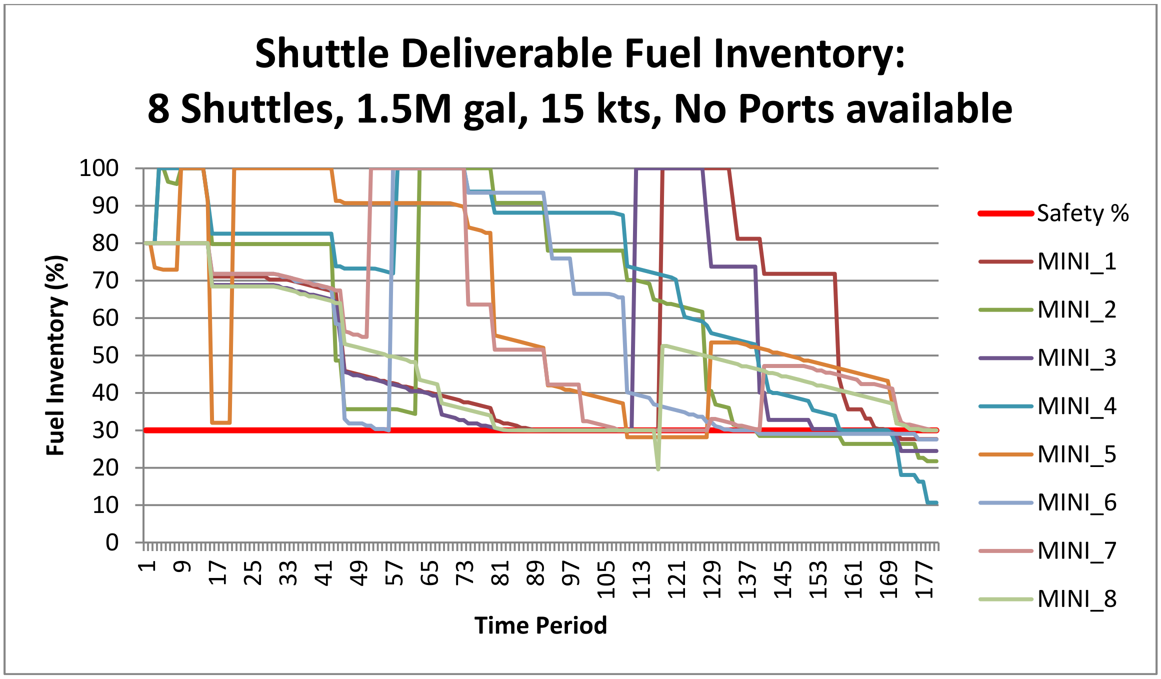


Figure 29. Shuttle deliverable fuel inventory levels during a 30-day time horizon utilizing eight shuttles with 1.5 M-gallon deliverable fuel quantity and no ports available

The percentage of time spent on station, transiting or waiting, and actively refueling, for each warship are given in Table 15. Although there is a small degradation in performance relative to the design point of six shuttles with no ports available (quantified in Table 16), we see that this design point nearly recovers that level of performance and may be considered adequate for a wartime scenario, assuming no ships are lost.

Table 15. Warship employment when eight shuttles are available, each with a 1.5 M-gallon deliverable fuel capacity, and port access is restricted

| Percentage | DDG_1 | DDG_2 | DDG_3 | DDG_4 | DDG_5 | DDG_6 | CG_1 | CG_2 | CG_3 | CG_4 | CVN_1 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time on FOS | 71.1 | 71.1 | 71.1 | 74.4 | 73.3 | 73.9 | 71.7 | 72.8 | 73.9 | 73.3 | 72.2 |
| Transit/Wait Time | 23.3 | 22.8 | 21.7 | 21.7 | 22.2 | 21.1 | 22.8 | 22.2 | 22.2 | 22.8 | 21.1 |
| Active RAS | 5.6 | 6.1 | 7.2 | 3.9 | 4.4 | 5.0 | 5.6 | 5.0 | 3.9 | 3.9 | 6.7 |

Table 16. Percentage of time change per given activity from six shuttles and 1.5 M-gallon deliverable fuel each with ports not available to replenish shuttles to eight shuttles and 1.5 M-gallon of deliverable fuel quantity each with no ports

| Percentage | DDG_1 | DDG_2 | DDG_3 | DDG_4 | DDG_5 | DDG_6 | CG_1 | CG_2 | CG_3 | CG_4 | CVN_1 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time on FOS | 6.1 | 5.0 | 6.7 | 2.8 | 1.7 | 1.7 | 5.6 | 6.7 | 2.2 | 0.0 | 5.6 |
| Transit/Wait Time | -7.2 | -5.6 | -8.3 | -1.1 | -1.1 | -1.1 | -6.7 | -7.8 | -1.1 | 0.0 | -1.7 |
| Active RAS | 1.1 | 0.6 | 1.7 | -1.7 | -0.6 | -0.6 | 1.1 | 1.1 | -1.1 | 0.0 | -3.9 |

An average increase of 4.0% Time on FOS, equating to 28.8 hours per warship during the 30-day planning horizon is shown in Table 16. It also indicates an average decrease of 3.8% Transit/Wait Time and 0.2% Active RAS time, resulting in a decrease of 27.3 hours and 1.5 hours per warship for the given activity, respectively.

As displayed in Table 17, the change in percentages from the design point of six shuttles and 1.5 M gallons of deliverable fuel with ports available for shuttle replenishment and the design point of eight shuttles and 1.5 M gallons of deliverable fuel with no ports available for shuttle replenishment

Table 17. Change in warship employment from the six shuttle design point with ports available to the eight-shuttle design point with ports unavailable, as a percentage of the 30-day time horizon

| Percentage | DDG_1 | DDG_2 | DDG_3 | DDG_4 | DDG_5 | DDG_6 | CG_1 | CG_2 | CG_3 | CG_4 | CVN_1 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Time on FOS | -2.2 | -2.2 | -2.2 | -2.8 | -2.8 | -2.8 | -1.7 | -0.6 | -3.3 | -3.9 | -1.1 |
| Transit/Wait Time | 1.7 | -0.6 | -1.7 | 2.2 | 1.7 | 1.1 | -0.6 | -1.1 | 2.2 | 2.8 | -1.1 |
| Active RAS | 0.6 | 2.8 | 3.9 | 0.6 | 1.1 | 1.7 | 2.2 | 1.7 | 1.1 | 1.1 | 2.2 |

We see that the loss of port availability causes an average decrease of 2.3% Time on FOS, equating to a decrease of 16.7 hours per warship during the 30 day planning horizon. We also note an average increase of 0.6% Transit/Wait Time and 1.7% Active RAS time, corresponding to an increase of 4.3 hours and 12.4 hours per warship for the given activities, respectively. The addition of the two shuttles shifts warship employment back towards the six-shuttle scenario when ports were available, though it does not close the gap entirely.

Although we do not explicitly seek to optimize fuel efficiency, it is still of interest to examine this aspect of performance. Thus, we calculate the quantity of fuel burned per gallon of fuel delivered in each scenario utilizing the following equations, where $Burned_s$ is the total amount of fuel burned by shuttle $s$ during the 30-day horizon, $Burned_c$ is the corresponding quantity for CLF $c$, and $Delivered_w$ is the total amount of fuel delivered to warship $w$:

$$\sum_s Burned_s = \sum_s \left( \left( INV_s^1 - INV_s^{180} \right) + \sum_t \left( HOLD\_INV_s^t + INPs_s^t + \sum_c RAS\_burn\_s_{s,c}^t \right) \right)$$

$$\sum_c Burned_c = \sum_c \left( \left( INV_c^1 - INV_c^{180} \right) + \sum_t \left( HOLD\_INV_c^t + INPc_c^t \right) \right)$$

$$\sum_w Delivered_w = \sum_{t,w,s} RASw_{w,s}^t + \sum_{t,w} INPw_w^t$$

$$Ratio = \left( \sum_s Burned_s + \sum_c Burned_c \right) / \sum_w Delivered_w$$

When ports are available and we have six shuttles with 1.5M gallons capacity, we calculate that *Ratio*=0.46. That is, for every gallon of fuel delivered to a warship, we burn 0.46 gallons transporting it. In the heightened threat scenario (no ports available) with the same shuttle design point, this figure increases to 0.54 gallons. Finally, in the heightened threat scenario with eight shuttle ships, we find that *Ratio*=0.66. This increase reflects the additional burden of transiting to the ARLs vice nearby ports, as well as the impact of having more shuttle ships present and burning fuel.

Recall that the LCS/JHSV has been suggested as a possible candidate for a shuttle platform.

LCS 2 and JHSV have planning factor fuel capacities of 2,663 bbls (111,846 gals) and 3,745 bbls (157,290 gals), respectively (Trickey & Grenwald, 2014). Clearly, these values do not come close to our identified design point of 1.5M gallons deliverable fuel capacity. Even with a proposed 20% increase in fuel capacity as possibly provided by an installed logistics module, their configuration and capabilities do not meet the design requirement for this scenario. Therefore, LCS and JHSV appear to lack the ability to adequately support deployed CTF/CRUDES SAG assets in the 7th Fleet A2AD environment.

We find that six shuttle ships with 1.5M gallons of deliverable fuel can adequately fill the role as a “delivery boy” in a 7th Fleet A2AD environment, assuming ports are available to replenish the shuttles. In a heightened threat environment when no ports are available to replenish shuttles in our scenario, eight such shuttles are required for sustainable support.

# V. CONCLUSIONS, RECOMMENDATIONS AND FOLLOW-ON STUDIES

## A. CONCLUSIONS

The most important finding in our study is the effectiveness of DL-RASM to provide decision support to the decision maker in determining theater level logistics and CLF shuttle requirements. DL-RASM is flexible enough to model a variety of scenarios, and it solves quickly enough to enable detailed sensitivity analysis. Thus, it can provide senior decision makers with an improved understanding of fleet requirements for logistic support, and it can inform future CLF force structure decisions.

In our peacetime scenario, we demonstrate how the deliverable fuel quantity and number of shuttles affects the shuttles ability to support the deployed forces. Our analysis does not indicate a strong correlation between increased shuttle speed and an improved ability to support the warships. While speed does not play a decisive role in our scenario, increased shuttle speed may have other positive influences in other scenarios. For instance, it may allow for improved evasive maneuvering or other defensive measures.

Our analysis indicates that a moderate number of shuttles is required to support a peacetime scenario and can allow some resiliency should a wartime scenario ensue. A larger number of shuttles are required to provide sustainable support in a wartime scenario. Indeed, perhaps our most interesting findings result from eliminating the vulnerable ports as a replenishment option for the shuttles. We find that the required number of shuttles during peacetime cannot support the warships without port access. Additionally, we find that the efficiency of delivering fuel is dependent upon the number of shuttles available and that efficiency and effectiveness are competing objectives that must be balanced.

## B. RECOMMENDATIONS

For our developed scenario in the 7th Fleet AOR, and analysis completed during both peace and wartime situations, we recommend continued research into developing a CLF shuttle ship with a deliverable fuel capacity of approximately 1.5M gallons. Such a vessel could be employed in a fleet composition of six and eight shuttles in a peace and wartime scenario, respectively, for a deployed warship fleet configuration of one CTF and one CRUDES SAG.

## C. FOLLOW-ON STUDIES AND IMPROVEMENTS

Recommendations for follow-on work are as follows:

### 1. Expansion to Multi-commodity Flow Model

For simplicity, we model liquid fuel as a single commodity combining the DFM and JP5 requirements of surface ships and a deployed airwing on a carrier. To improve DL-RASM's accuracy, we recommend expanding it to a multi-commodity flow model.

### 2. User Interface Development

We recommend development of a user interface or scenario developer for DL-RASM. This would make DL-RASM more user-friendly and could ultimately increase its level of employment.

### 3. Mini-CLF Development Cost Analysis

Development of new platforms requires not only dimension analysis and engineering, but also cost analysis. A cost analysis of the proposed CLF shuttle would provide further insight into the feasibility of adopting and employing the dual-RAS lane concept of operations.

### 4. Scenario Diversification

As we have only studied the use of DL-RASM in the 7$^{th}$ Fleet AOR, we recommend implementation of additional scenarios, to include alternate regions and evaluation of a Battle of the Littorals scenario. Such analysis can lend further credibility to the research and findings of this study and provide additional value to the adoption of the concept of using CLF shuttles.

# APPENDIX. NEARLY ORTHOGONAL LATIN HYPERCUBE (NOLH) DESIGN OF EXPERIMENTS (DOE)

| Design Point | Speed (kts) | Deliverable Fuel Qty. (gals) | # of Shuttles | Optimal Objective Value |
|---|---|---|---|---|
| 1 | 13 | 750000 | 4 | -49701107.7 |
| 2 | 13 | 1000000 | 6 | -14389238.2 |
| 3 | 19 | 750000 | 6 | -51560310.6 |
| 4 | 17 | 750000 | 7 | -243709000.0 |
| 5 | 17 | 1250000 | 3 | -44309779.1 |
| 6 | 15 | 1500000 | 5 | -2116539.6 |
| 7 | 15 | 1000000 | 8 | -37235850.5 |
| 8 | 17 | 1000000 | 4 | -58387615.4 |
| 9 | 15 | 1500000 | 7 | -4115407.8 |
| 10 | 13 | 1250000 | 7 | -23225770.8 |
| 11 | 17 | 1000000 | 5 | -119006000.0 |
| 12 | 19 | 1250000 | 8 | 1259889.9 |
| 13 | 15 | 1000000 | 6 | -13723848.3 |
| 14 | 15 | 1250000 | 6 | 311896.4 |
| 15 | 17 | 1500000 | 6 | 1483891.5 |
| 16 | 19 | 1000000 | 7 | 179154.4 |
| 17 | 19 | 750000 | 5 | -35726192.6 |
| 18 | 13 | 1250000 | 5 | -38715229.2 |
| 19 | 13 | 1500000 | 8 | -2927663.1 |
| 20 | 15 | 1250000 | 4 | -3085296.6 |
| 21 | 17 | 1250000 | 8 | 707366.4 |
| 22 | 13 | 1000000 | 3 | -148675000.0 |
| 23 | 19 | 1500000 | 4 | -8166286.8 |
| 24 | 15 | 750000 | 3 | -253934000.0 |
| 25 | 19 | 1500000 | 3 | -3391122.4 |

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